

Predicting growth and future yield in *Eucalyptus grandis* x *urophylla* stands using the CABALA process-based model



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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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Summary

The aims of this research were to (1) partly parameterise and initialise and (2) test the CABALA process-based model for hybrid *Eucalyptus grandis* x *urophylla* clones in the Zululand region of South Africa. To achieve these aims, detailed data were obtained from a set of 18 sites at which permanent sample plots had been monitored for seven or more years. In July 2018, a data acquisition campaign was undertaken and diameter at breast height (DBH), and the heights of all trees at all sites were measured, soil samples taken, and leaf area index estimated using a LP80- ceptometer from all 18 sites. Destructive biomass measurements and collection of biomass subsamples were done at a subset of five sites in order to determine allometric parameters. Leaf area index was also obtained for all 18 compartments using the MODIS product provided by NASA. A set of experiments in nursery and laboratory environments were also undertaken to determine minimum pre-dawn leaf water potential, and the relationship between leaf nitrogen content and specific leaf area. Partial parameterisation of 17 parameters of the model for *Eucalyptus grandis* x *urophylla* was done by building on the existing *E. globulus* parameter set. This parameter set was altered using parameter data from published literature, allometric parameters obtained from field measurements and destructive sampling, using parameters obtained from experiments executed in the nursery and glasshouse, and by undertaking a limited calibrating/optimisation exercise.

The model was run using two sources of weather data: (1) long-term mean weather data (1949-1999) obtained from South African Atlas of Climatology and Agro- Hydrology weather data (2) and daily weather data (2008-2018) obtained from a variety of weather stations from South African Sugarcane Research Institute (SASRI) and Mondi, VitalWeather Systems and the South African Weather Services (SAWS). The long-term mean weather data

represented conditions in which there was no drought whereas the period 2008 – 2018 was one in which the region experienced a record-breaking period of drought. Hence these two datasets provided an interesting contrast.

The output from CABALA predictions were compared to observed stand volume, mean diameter at breast height, and mean height for the 18 study sites. Overall, when the long-term mean monthly weather data were used, CABALA overestimated stand mean diameter at breast height, mean height, and stand volume. When the daily weather data measured during the period when the trees actually grew (2008 – 2018) was used, the model gave better estimations of mean diameter at breast height but tended to underestimate mean height and stand volume, especially on higher productivity sites that generally received high mean annual precipitation. The leaf area index estimated by CABALA was compared to estimates from the MODIS LAI product and while CABALA overestimated leaf area index in many instances, it predicted the leaf area index drop trend observed during the drought period 2014-2016 as soon as the daily weather conditions were introduced. The model with its modified parameter set underestimated mortality in all sites irrespective of weather conditions.

Opsomming

Die doelwitte van hierdie navorsing was om (1) gedeeltelik te parameteriseer en te initialiseer en (2) die CABALA-prosesgebaseerde model vir baster *Eucalyptus grandis* x *urophylla*-klone in die Zululand-streek in Suid-Afrika te toets. Om hierdie doelstellings te bereik, is gedetailleerde data verkry vanaf 'n stel van 18 terreine waarop permanente steekproefpersele vir sewe of langer jare gemonitor is. In Julie 2018 is 'n data-verkrygingsveldtog onderneem en deursnee op borshoogte (DBH), en die hoogtes van alle bome op alle terreine is gemeet, grondmonsters geneem en die blaaroppervlakte-indeks geskat met behulp van 'n LP80-ceptometer van al 18 terreine. Vernietigende biomassametings en versameling van biomassa-submonsters is op 'n subversameling van vyf terreine gedoen om allometriese parameters te bepaal. Blaaroppervlakte-indeks is ook vir al 18 kompartemente verkry met behulp van die MODIS-produk wat deur NASA verskaf is. 'N Stel eksperimente in kwekerye en laboratoriumomgewings is ook onderneem om die minimum potensiaal voor die dagbreek van die blaarwater te bepaal en die verband tussen die stikstofinhoud van die blaar en die spesifieke blaaroppervlakte.

Gedeeltelike parameterisering van 17 parameters van die model vir *Eucalyptus grandis* x *urophylla* is gedoen deur voort te bou op die bestaande *E. globulus* parameterset. Hierdie parameterset is verander deur gebruik te maak van parametergegewens uit gepubliseerde literatuur, allometriese parameters verkry uit veldmetings en vernietigende steekproefneming, met behulp van parameters verkry uit eksperimente wat in die kwekery en kweekhuis uitgevoer is, en deur 'n beperkte kalibrasie- / optimaliseringsoefening te onderneem.

Die model is gebruik met behulp van twee bronne van weerdata: (1) gemiddelde langdurige weerdata (1949-1999) verkry uit die Suid-Afrikaanse Atlas van Klimatologie en Agro-Hidrologie weerdata (2) en daaglikse weerdata (2008-2018) verkry vanaf 'n verskeidenheid weerstasies van die South African Sugarcane Research Institute (SASRI) en Mondi

VitalWeather Systems en South African Weather Services (SAWS). Die langdurige gemiddelde weerdata verteenwoordig toestande waarin daar geen droogte was nie, terwyl die periode 2008 - 2018 'n periode was waarin die streek 'n rekordgetroue periode van droogte beleef het. Hierdie twee datastelle het dus 'n interessante kontras gelewer.

Die uitsette van CABALA-voorspellings is vergelyk met die waargenome standvolume, gemiddelde deursnee op borshoogte en gemiddelde hoogte vir die 18 studiepersele. Oor die algemeen het CABALA die gemiddelde gemiddelde deursnee op borshoogte, gemiddelde hoogte en standvolume oorskat toe die gemiddelde gemiddelde maandelikse weerdata gebruik is. Wanneer die daaglikse weerdata gemeet is gedurende die periode waarin die bome werklik gegroei het (2008 - 2018), is die model beter geskat oor die gemiddelde deursnee op borshoogte, maar die gemiddelde hoogte en standvolume is onderskat, veral op plekke met hoër produktiwiteit wat gewoonlik hoë gemiddelde jaarlikse neerslag ontvang. Die blaaroppervlakte-indeks wat deur CABALA geskat is, is vergelyk met ramings van die MODIS LAI-produk, en hoewel CABALA in baie gevalle die blaaroppervlakte-indeks oorskat het, het dit die voorspelling van die dalingstendens van die blaaroppervlakte-indeks voorspel gedurende die droogteperiode 2014-2016 sodra die daaglikse weersomstandighede ingestel is. Die model met sy gewysigde parameterset het die sterfte op alle terreine onderskat, ongeag die weersomstandighede.

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Preface

This thesis is presented as a compilation of five chapters.

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GENERAL INTRODUCTION AND PROJECT AIM

1.1. Background of research

South African forest plantations stretch over several provinces: Limpopo, Mpumalanga, KwaZulu Natal, Eastern Cape and Western Cape Province of South Africa (see **Figure 1.1**) but cover only about 1 % (1.2 million hectares) of the country's land area (Edwards, 2012). The main species used by the forestry industry consist of pines, eucalypts and wattle which make up 51 %, 42 %, 7 % of the plantations, respectively. The two dominating genera, *Pinus* and *Eucalyptus*, are primarily managed for sawtimber and pulpwood respectively (Forestry economics services CC, 2016/2017).

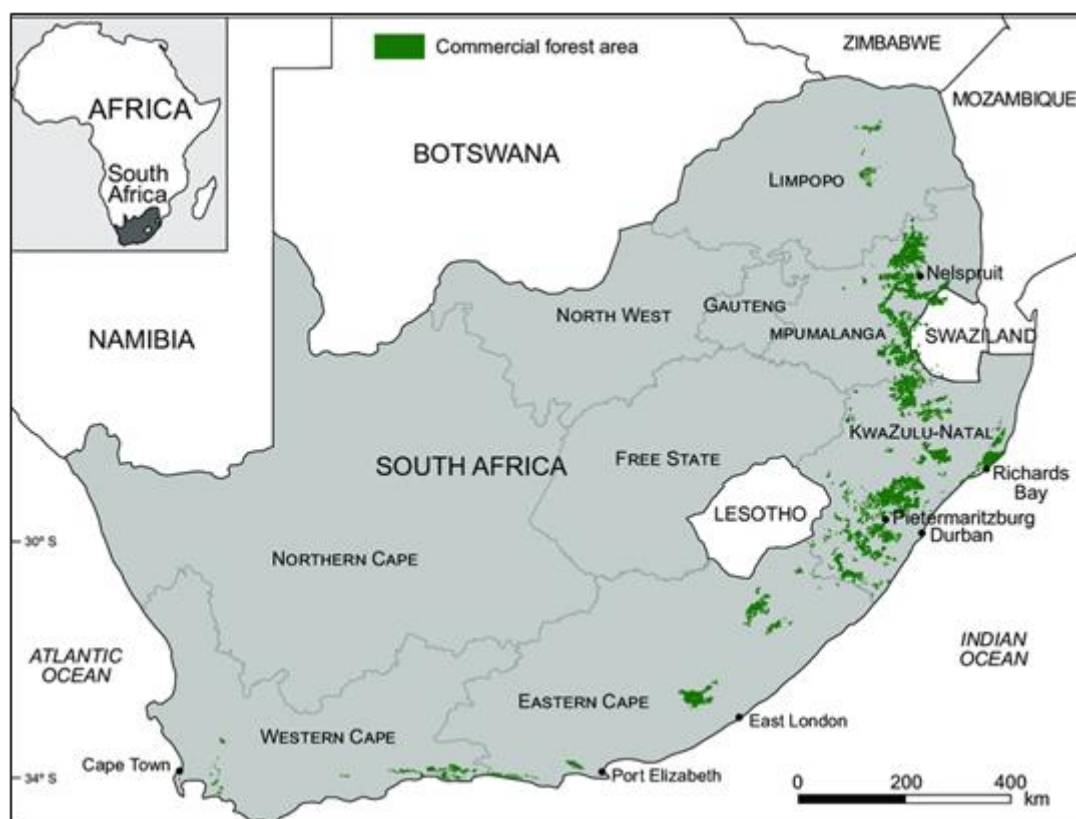


Figure 1.1: The distribution of plantations in South Africa by Xulu et al., (2018).

A large proportion (about 300,000 ha, 60 %) of South Africa's eucalypt resource is grown in KwaZulu-Natal province of South Africa (Forestry economics services CC, 2016/2017).

Eucalyptus nitens, *Eucalyptus macarthurii*, *Eucalyptus dunnii* and *Eucalyptus grandis* are the four pre-dominant non-hybrid commercial eucalypt species (Melesse & Zewotir, 2017) in the province.

The summer rainfall area of subtropical Zululand (mean annual temperature of 21 °C and mean annual precipitation of 1200 mm) is home to subtropical *Eucalyptus grandis* and *Eucalyptus grandis* hybrids which make up 73.8 % of eucalypt plantations planted in the region (Melesse & Zewotir, 2017). Hybrid clones, predominately *Eucalyptus grandis* x *Eucalyptus urophylla* (GU), are the main resource on the flat coastal plain with deep, aeolian sandy soils of Zululand (Dube, et al., 2015). These hybrid clones have largely replaced “pure” *Eucalyptus grandis* plantations on all coastal subtropical sites of Zululand (Crous & Burger, 2015). This was due to the hybrid’s improved pest and disease resistance linked with fast growth and satisfactory stem form (Melesse & Zewotir, 2017).

However, GU mortality is considered an issue on drought susceptible sites; for example, on drought-susceptible sites during the El Niño phase in 2010, GU mortality was much higher than on well-watered sites (Crous, et al., 2017). **Figure 1.2** illustrates another drought event which started from 2014 and ended in 2016 that led to major reduction in Normalized Difference Vegetation Index in GU stands located on drought-prone sites (Xulu, et al., 2018).

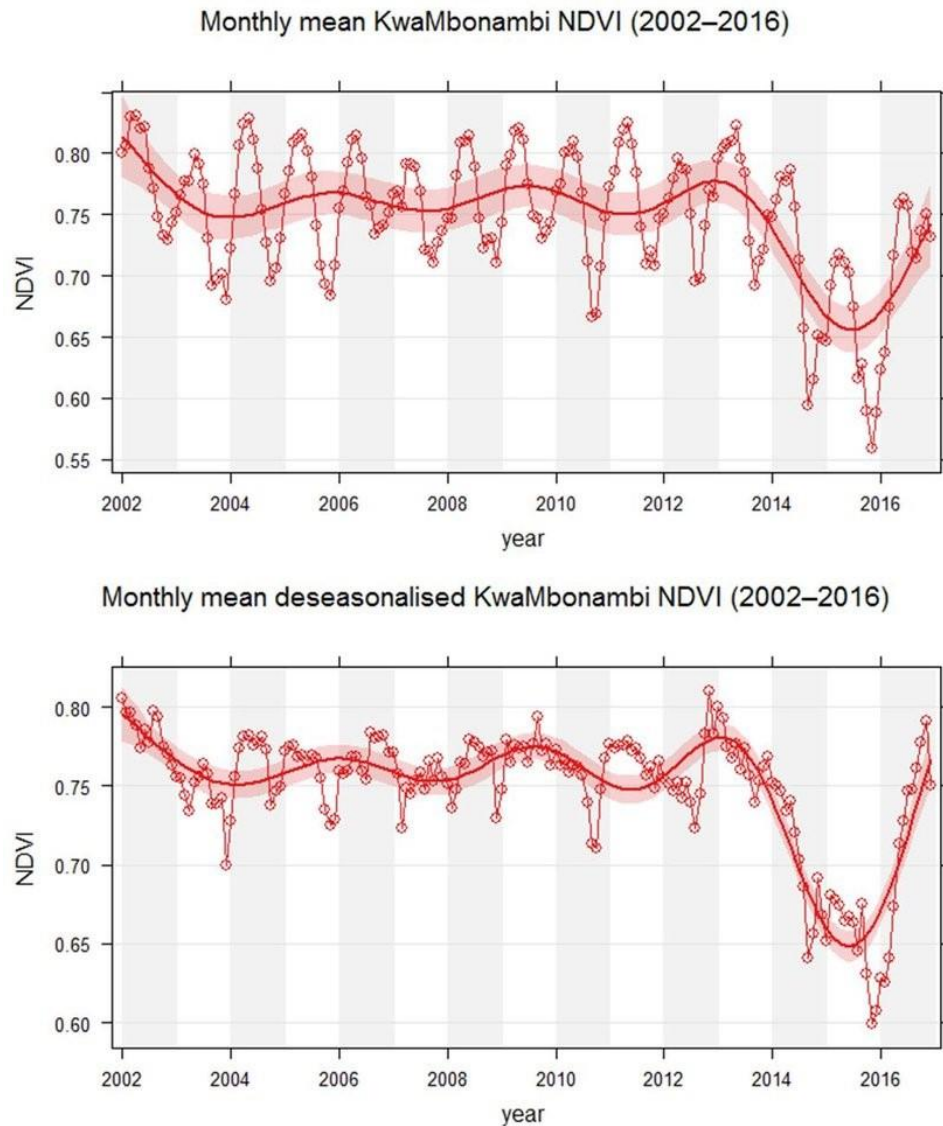


Figure 1.2: Smoothed and de-seasonalised NDVI time series (2002-2016) by Xulu et al (2018).

1.2. Modelling growth

The hybrid GU clone is sustainably and extensively managed in Zululand to produce optimum stand volume for the pulp industry. To achieve these goals, the most suitable silvicultural regime must be selected and applied for each compartment. Adequate planning of rotations and expected yield requires that good and reliable models be applied (Irfan

Ashraf, et al., 2015) and traditional empirical models are still widely used for this purpose (Dye, et al., 2004).

Although the reality is a continuum, two main types of model are typically distinguished in predicting forest growth and yield: empirical and process-based methods (Pretzsch, 2009). A third category is also defined: so-called hybrid models combine both empirical and process-based concepts (Weiskittel, et al., 2011).

Empirical models are statistical relationships or equations developed from data that has been observed. Empirical models are well known for being precise, robust and simple to apply (Korzukhin, et al., 1996), but they are developed under a specific time period and species rotation making the model temporary and site specific (Miehle, et al., 2009). This means that the application of empirical models is limited to a range of conditions. Using them in “green field” establishment can result in errors as previous inventory data are not available. In future rotations, where silviculture or climate changes, these models are often not sufficiently flexible (Miehle, et al., 2009).

Process-based models are, by contrast, constructed from knowledge of theoretical plant physiological processes and physical interaction with the surrounding environmental conditions, making these models sensitive to how environmental conditions change (Seely, et al., 2015) and theoretically applicable to green field forest establishment situations (Korzukhin, et al., 1996). Process-based models have been widely used to predict how forest ecosystems may respond to climate change in terms of productivity (Reyer, et al., 2016). On the other hand, process-based forest models are criticized for being impractical as they require detailed species parameters and input data which are not often readily available (Mäkelä, et al., 2000).

Hybrid models are growth and yield forecast models that combine empirical- with process-based elements to reduce the complexity of process-based models yet taking advantage of the simplicity of empirical models (Irfan Ashraf, et al., 2015). This way, both models' shortcomings are minimized to some degree.

The value of process-based models, particularly some of the more complex types, has still not been clearly demonstrated for South African plantations. Some work has been done (see in **Chapter 2**), but only in a limited context. This study was set up in response to interest from growers of short rotation eucalypts in the application of process-based forest models for forecasting growth and yield in South African plantations. In particular, there was interest in the CABALA model of Battaglia et al. (2004), the application of which has not been explored at all in South Africa. Given the value of the GU resource in the Zululand area, and following discussions with industry growing in this area, this study was developed to set up and test the CABALA model. The study focused on *Eucalyptus grandis* x *urophylla* hybrid stands in the Zululand region. The objectives of the research project are to:

- Develop a dataset for setting up and testing the model,
- Develop a partially revised parameter set for CABALA for GU, and
- Test the model under a range of conditions and with varied data inputs.

LITERATURE REVIEW

2.1. Process-based models as an approach to predicting forest growth

Process-based forest models aim to estimate growth and yield based on the knowledge of theoretical plant physiological processes and physical interaction with the surrounding environmental conditions (see *Figure 2.1*). These process-based forest models may vary in complexity and the purpose they aim to serve. Weiskittel et al. (2011) defined six “pillars” on which process-based models are almost invariably built. These are light interception, photosynthesis, stomatal conductance, carbon allocation, and water relations and nutrients. A brief description of these six “pillars” is given below as it serves as a useful background for understanding the CABALA framework.

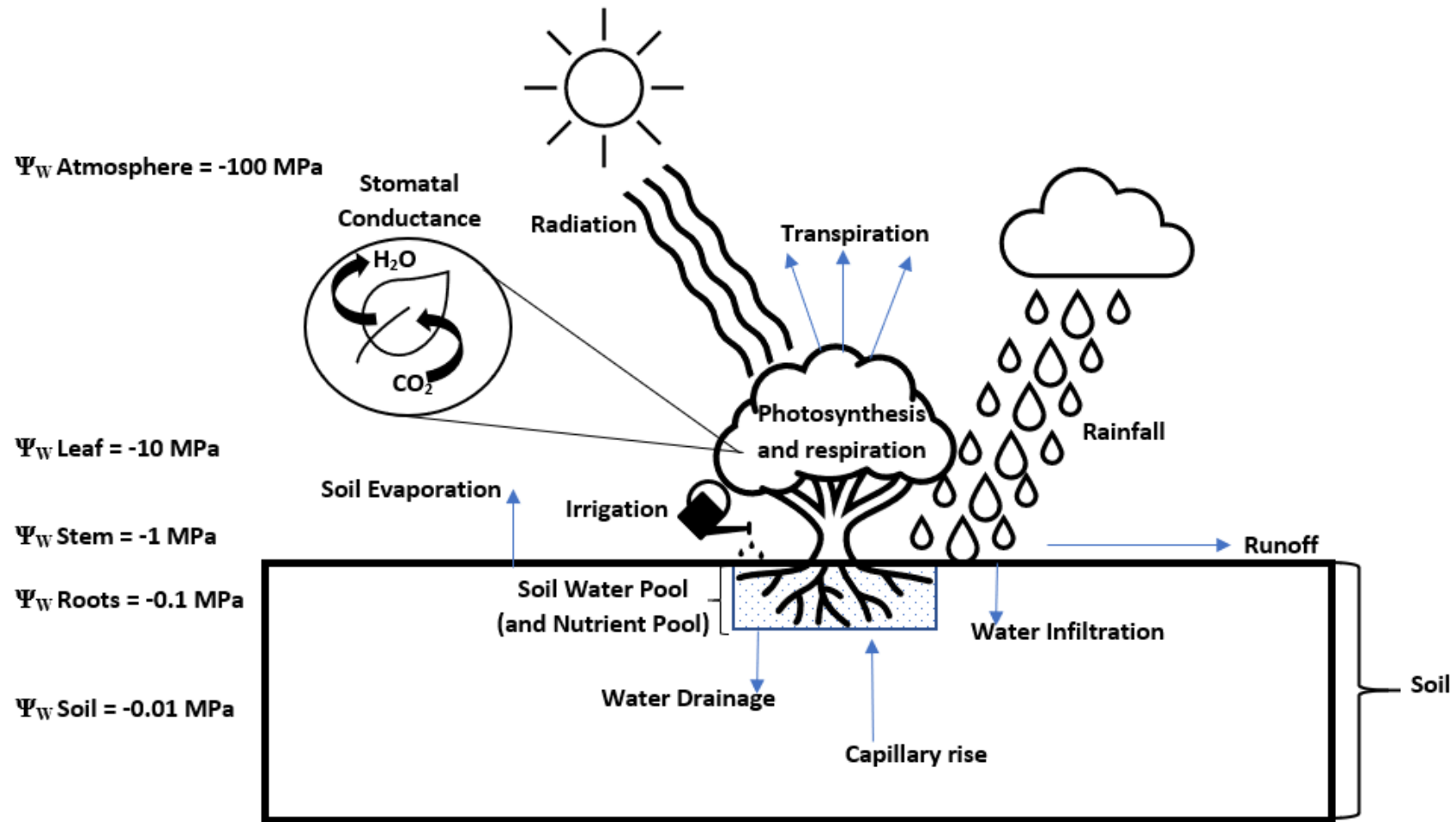


Figure 2.1: General physiological processes and physical interactions in the soil- plant- atmosphere continuum observed in process-based models. Respiration is not limited to foliage, it may also be in other tree compartments such as branch, stem, and roots. The blue arrows indicate the direction of water movement.

2.1.1. The “six pillars”

2.1.1.1. *Light interception*

Light interception has a strong, positive, linear relationship with canopy production (McCrary & Jokela, 1998). Light interception may be estimated by the modified Beer-Lambert law of light extinction for tree canopies which states that light interception attenuates exponentially with depth in a canopy if it is assumed that foliage in the canopy is homogeneous, randomly distributed, foliage inclination angles are spherically distributed in space, and woody plants of the canopy are negligible (Weiskittel, et al., 2011).

Process-based forest models assume that light is homogeneous and adopt a constant extinction coefficient regardless of the dynamic nature of the extinction coefficient during the day and with seasons and sky cloud cover. Brèda et al., (2003) reported a constant extinction coefficient of 0.40 and 0.47 in average for coniferous and broad-leaved stands respectively which were measured globally; the lower extinction coefficient in coniferous stands is due to their large clumping factor (Brèda, 2003).

2.1.1.2. *Photosynthesis*

Photosynthesis is the process by which plants use light energy to convert carbon dioxide and water to carbohydrates. To predict tree growth in a process-based model we must first model photosynthesis.

Photosynthesis can be estimated from the measurable non-linear photosynthetic light-response curve (Xu, et al., 2019; Ögren & Evans, 1993). The photosynthetic light-response curve represents the relationship between photosynthetic rate and the available photosynthetic photon flux density at leaf level (Liu, et al., 2019). The most utilized mathematical models for describing the

photosynthetic light-response curve are the rectangular hyperbolic Michaelis-Menten model, hyperbolic tangent models, the exponential models, the Ye model and the non-rectangular hyperbola-based models (Lobo, et al., 2013).

Photosynthesis can be relatively simply estimated from the light-response curve using the empirical non-rectangular hyperbola equation which consists of three parameters indicating the initial slope, the asymptote and a third parameter, not present in the other mentioned models, for adjusting the non-linearity of the leaf response to light (Thornley, 2002).

A more complex approach is the biochemically based Farquhar equation for estimating carbon assimilation at leaf level under ambient carbon dioxide (CO_2)-and oxygen (O_2) concentrations (Morales, et al., 2005; Landsberg, 2003). The main drivers of Farquhar photosynthesis parameters are the maximum carboxylase capacity of the leaf and the light intensity dependent electron transfer capacity (Walker, et al., 2014) which are both sensitive to temperature.

Of course, not all foliage within a canopy receives the same amount of light, so whichever model is applied there is a need to integrate photosynthesis over a large and variably irradiated canopy. There are three different approaches to integrate the leaf photosynthesis to canopy photosynthesis: the big leaf model, single layer of sunlit and shaded model, and the multi-layer model:

- The big leaf model treats the canopy as one big leaf to estimate canopy fluxes (leaf energy, water and CO_2) by coupled equations whilst requiring a known total amount of nitrogen and specific leaf area, and constant parameter adjustment to avoid identical big leaf and single leaf responses caused low leaf area index (LAI) (Ding, et al., 2014).
- The single layer of sunlit and shaded model is big leaf model which estimates fluxes separately with parameters determined by using integrals through the canopy. Only the sun leaves receive diffuse and direct irradiance assuming that scattered sunlight to diffuse light is ignored (Ran, et al., 2017).

- The multi-layer model estimates the total flux by integrating the flux from different canopy layers; parameters of the model can be obtained from direct measurements (Wu, et al., 2017).

2.1.1.3. Stomatal conductance

Stomatal conductance is an estimate of the rate at which CO₂ and water vapour are exchanged between the leaf and atmosphere (Giménez, et al., 2005) through the stomata. Stomatal conductance is dependent on vapour pressure deficit (VPD) (Ocheltree, et al., 2014), temperature (Urban, et al., 2017), soil water status and radiation (Pieruschka, et al., 2010). The Ball-Berry model, which shares parameters with some of the leaf photosynthesis model, is used in many process-based forest models to determine leaf level stomatal conductance (Farquhar & Sharkey, 1982). However, the Ball-Berry model does not explicitly take the influence of soil water deficit into consideration. The model works better under adequately watered conditions and does not describe the effect of drought on stomatal closure (Dewar, 2005). Canopy conductance is determined as the product of stomatal conductance and LAI treating the canopy as one big leaf (Weiskittel, et al., 2011).

In principle, an increase in water demand increases evapotranspiration of plants; to which plants respond to by closing their stomata to reduce evapotranspiration with the aim of conserving water (Massmann, et al., 2019). When water is abundant, a plant will transpire water from the soil to the air to meet the atmospheric demand (Asbjornsen, et al., 2011). In a case of restricted water, stomata are reduced, and CO₂ is not absorbed meaning that photosynthesis cannot take place, and production is compromised.

Transpiration rate is higher at more intense radiation levels and high wind speed resulting, ultimately, in stomatal closure. The Penman-Monteith model is popular in many process-based forest models to scale up transpiration from leaf-level measurements to tree crown. Penman-Monteith model is driven by mean temperature, wind speed, relative humidity, and canopy

conductance (Waring & Running, 2007), however, this model is prone to overestimating due to the absence of soil water deficit on stomatal closure in Ball-Berry equation (Weiskittel, et al., 2011).

2.1.1.4. Autotrophic respiration

Net primary production is defined as the difference between photosynthesis and autotrophic respiration (Pan, et al., 2014). A simple approach taken in some process-based forest models is to “tax” the plant by separating respiration from the gross photosynthesis as a constant fraction: gross photosynthesis ratio (Thornley, 2011). The respiration: gross photosynthesis ratio ranges between 0.35-0.6 and is conservative over tree age and size, temperature growth rate, and CO₂ concentration (Gifford, 2003).

Other process-based models account for respiration as a combination of growth respiration and maintenance respiration, otherwise known as the maintenance and growth respiration paradigm (Ryan & Asao, 2019). Growth respiration is effective for synthesising new biomass and maintenance respiration for the maintenance of existing biomass produced in plants. Unlike growth respiration, maintenance respiration is dependent on temperature and increases exponentially with temperature, thus warmer climates may cause an increased maintenance respiration tax (Ryan & Asao, 2019). Maintenance respiration can be modelled based on dry matter or nitrogen turnover (Thornley & Cannell, 2000).

The respiration sensitivity to temperature is typically modelled using the so-called Q_{10} function, defined as the respiration rate at a temperature divided by the respiration rate at a temperature 10 °C lower (Fusaro, et al., 2019). Most respiration models assume a sensitivity of specific respiration of $Q_{10} > 2$, however the acclimated Q_{10} may be less than 2 (Gifford, 2003). Long-term Q_{10} tend to be lower than the acclimated short- term Q_{10} , hence, it is important to note that short-term respiration response to temperature change does not estimate their long-term temperature response (Gifford, 2003).

2.1.1.5. Carbon allocation

Process-based models must incorporate an aspect which decides where in trees the photosynthate should be allocated to. The type of carbon allocation model selected for a specific process-based model is based on the primary objectives of the respective process-based model. Following are a description of the type of carbon allocation models process-based models can adopt to estimate carbon allocation.

So-called coordinated-and goal-oriented-based models are commonly used in process-based forest models for allocating the fixed photosynthetically assimilated carbon (C) to different growth components of a tree including foliage, fine roots and wood (Weiskittel, et al., 2011).

Coordinated models, which take a functional balance approach, aim to balance out limiting effects of different resources by prioritizing the allocation of carbon to the tree component responsible for obtaining the most limiting resource (Franklin, et al., 2011). The shoot: root functional balance and pipe model are carbon allocation model types that take a functional balance approach (Merganičová, et al., 2019).

In the shoot: ratio functional balance model assimilated carbon is allocated to growth components to secure a balanced supply of resources from the foliage and fine roots (Sievänen, et al., 2000).

Whereas the pipe model allocates assimilated carbon to ensure that the required total conductance in the sapwood is appropriate for the foliage (Franklin, et al., 2011). The pipe model may be used along with the root: shoot functional balance equation or other allometric relationships (Merganičová, et al., 2019).

Goal-oriented based models are at plant level and aim to allocate assimilated carbon following an allometric rule based on relationships between dimensional variables such as tree height, stem length, diameter, leaf area, weight or volumes (Franklin, et al., 2011). Allometric rules generally form a multiplicative power function. So-called goal-oriented models include optimal response

which optimize the strategy of C allocation with the aim to maximize a growth rate in a stable environment (Le Roux, et al., 2001).

2.1.1.6. Soil water relations and nutrients

In the soil-plant-atmosphere continuum water is extracted from the soil by roots, transported into and through the plant, and released into the atmosphere through transpiration (García- Tejera, et al., 2017). This movement of water is guided by the water potential gradients which is initiated by water uptake from the leaves resulting in a water potential decrease in the leaves (Ranatunga, 2012). Hence, water moves from the highest water potential (the soil) to the lowest water potential (tree canopy).

Tree-water relation models estimate the soil-and leaf-water status (water content and water potential), and how water availability affects the tree physiological process and growth (Deng, et al., 2017). While most models neglect plant water storage (Ranatunga, 2012), soil water storage plays a major role in tree-water relation models.

Soil water balance or change in soil water content for a particular period is estimated for the soil in the root zone and is equals to the amount of water that enters the soil minus the amount of water that leaves the soil in the course of the period of interest (Zhang, et al., 2002). Water enters the soil in the root zone through capillary rise and infiltration or irrigation and/or precipitation that reaches the ground (Triegel & Guo, 2018). Water leaves the root zone through evapotranspiration, runoff, and deep drainage. Overflow and deep drainage occur when there is excess water in the root zone (Zhang, et al., 2002).

Root water uptake functions are classified into two approaches: microscopic and macroscopic (Luo, et al., 2003). A microscopic approach assumes that soil water is extracted by root systems assembled as pipes with axial and radial resistance (Deng, et al., 2017). In the macroscopic approach, water is extracted by the root system as a sink term, referring to water uptake, by

estimating water loss from each soil layer in the root zone at a rate which varies according to the site, water content and time (Luo, et al., 2003).

The Richards equation is a widely utilised macroscopic approach in process-based models to estimate root-water uptake in unsaturated soils (Skaggs, et al., 2006). A stress function may be applied in the Richards equation to estimate water uptake rate and impact of soil water deficit on transpiration. This stress function is dependent on the atmospheric demand, soil water status and prescribed stress function (Zhang, et al., 2002). Another approach used in the Richards equation to determine water uptake rates is the Darcy law which is driven by the soil potential gradients and hydraulic conductivity (Skaggs, et al., 2006).

Nitrogen is an important nutrient recognized in process-based forest models since leaf nitrogen content is associated with photosynthesis rate (Sharwood, et al., 2017), however, nitrogen availability is not estimated in most process-based models. Nevertheless, the CABALA process-based model explicitly attempts to estimate nitrogen availability and it plays an important role in estimating stand productivity. Biomass turnover and fertilizers are the primary nitrogen sources in the CABALA process-based-forest model and absorbed into the plants with water (Battaglia, et al., 2004). Nitrogen is assumed to be mobile with water in CABALA. Thus, nitrogen is taken up as a constant fraction of water and lost with deep drainage in excess of water (Battaglia, et al., 2004).

2.1.2. Summary of some common process-based forest models

Process-based forest models vary in model complexity and primary applications. Model complexity increases as more site variables and species-specific parameters are demanded by the model (Seely, et al., 2015). Ideally, this increased complexity should lead to increased prediction accuracy (Miehle, et al., 2010).

A number of models have been produced in the last three decades. Some well-known models include BIOMASS (McMurtrie & Landsberg, 1992), G'DAY (Comins & McMurtrie, 1993), 3-PG (Landsberg & Waring, 1997), 3PG+ (Morris & Baker, 2002), CABALA (Battaglia, et al., 2004),

CenW (Simioni, et al., 2009), Forest DNDC (Li, et al., 2005), etc. From these process-based models, only 3PG has been widely applied in South Africa previously for research purposes.

3-PG (Physiological Principles Predicting Growth) is a simple hybrid type model forest model developed with the purpose of predicting forest growth and development at the stand level. The model runs on a monthly time step using monthly climate input data namely: mean temperature in °C, mean VPD in mbar, mean precipitation in mm, mean solar radiation in MJ m⁻² day⁻¹ and mean number of frost days. 3-PG also predicts stand water use, soil water availability and biomass pools. The canopy production is affected by VPD, temperature, soil water, site nutrition, frost and stand age modifiers (Sands & Landsberg, 2002)

Simpler process-based, or hybrid models like 3-PG (Landsberg & Waring, 1997) are more broadly applicable and easier to calibrate than more complex model forms. A complexity ranking is proposed which allocates models to a class based on the number of site and species-specific parameters required (*Table 2.1*). *Table 2.2* shows a summary of a number of process-based forest models and their complexity level.

Table 2.1: A system for ranking the complexity of process-based forest models using levels. The model is considered to be more complex as the number of inputs data, including site description data and species specific-parameters, are required by the model.

Level of the model's complexity	Number of input data sets required by model
1	1-25
2	26-50
3	51-75
4	76-100
5	101+

Table 2.2: A summary of a number of process-based models and their relative complexity level according to Table 2.1.

Process-based forest model	Spatial resolution	Time step	Number of input parameters	Model Complexity
3-PG (Sands & Landsberg, 2002)	Stand level	Monthly	37	2
CABALA (Battaglia, et al., 2004)	Stand level	Daily and monthly	150	5
Forest-DNDC (Miehle, et al., 2006)	Stand level	Monthly	40	2
Mobile-PDT (Miehle, et al., 2010)	Stand level	Daily and monthly	38	2

2.1.3. Data requirements for Process-based modelling

Process-based forest models require input data in four main categories: information about the soil, the regime (how the forest was managed), weather and parameters which describe the physiological properties and limitations of the species being modelled:

- i. Soils: Soils data detail level differs between different process-based models. However, the soil data primarily describe the soil fertility and water holding capacity (Mäkelä, et al., 2000). An example of required soil data includes soil texture, soil depth, fertility (C:N ratio), organic carbon percentage, bulk density, etc. Process-based models with advanced soil-oriented models may require information about soil temperatures and previously mentioned soil data at different soil depths.

- ii. Regime: The regime must be specified before initialising process-based forest models as the regime will determine that initial stand density and final stand density and volume (Mäkelä, et al., 2000). Regime information should include stand density and/or establishment espacement, fertilising, pruning, thinning and weed control applied in the forest stand (Battaglia, et al., 2004).
- iii. Weather: Stand growth is highly affected by rainfall, radiation, VPD and temperatures (Suvorova, et al., 2017). Process-based models weather and climate data details range from daily-, short term monthly-, to long-term monthly data (Lobell & Asseng, 2017). The level of weather data details depends on the model's time step which is typically between hourly to monthly.
- iv. Species-specific parameters: Parameters data sets are species-specific and based on the six pillars of physiological processes found in process-based models (Weiskittel, et al., 2011) mentioned earlier in the chapter. As already mentioned, complex process-based models tend to have more species-specific parameters set than simplified models.

2.1.4. The application of process-based models in South Africa's forestry industry

3-PG is the widely applied hybrid-type model in South Africa and has been evaluated on several *Pinus* and *Eucalyptus* plantations of South Africa (Dye, et al., 2004). A parameter sensitivity analysis on 3-PG was done by Esprey et al. (2004) for *E. grandis* plantations in South Africa to highlight the crucial parameters that needs accurate estimations to ensure that 3-PG gives the best results when applied in South African *E. grandis* plantations (Esprey, et al., 2004). In general, 3-PG generated sound results showing a good correlation between observed and predicted stand volume in irrigation and fertilisation treatments (Campion, et al., 2005).

2.2. The CABALA model

2.2.1. Summary of CABALA

CABALA was initially developed as a support tool for managing Australian *Eucalyptus globulus* plantations (Battaglia, et al., 2004). The model evolved from a simpler process-based model, ProMod, (Sands, et al., 2000) which was, perhaps, more similar to 3-PG. CABALA has more sub-models than ProMod and 3-PG. This brief model description summary is based on Battaglia et.al. (2004). **Figure 2.2** illustrates the main interactions in CABALA.

2.2.1.1. CABALA as a plantation management tool

The CABALA process-based model has not yet been applied in South African plantations. This complex CABALA process-based forest model was primarily designed for management purposes and gave the highest model efficiency (0.7) compared to 3PG, 3PG+, Forest-DNDC, and Mobile-PDT which each gave a model efficiency of 0.57, 0.22, 0.3, and 0.58 respectively (Miehle, et al., 2010). Miehle et.al (2010) ranked CABALA as the most reliable model for silvicultural management decision model compared to the 3PG, 3PG+, and Forest-DNDC. Higher precision of growth and yield prediction in CABALA is due to its complexity and high demand for input data including soil data, climate data and underground tree biomass data which is not readily available (Miehle, et al., 2009). These observations of the CABALA model demonstrate that CABALA is a potential model to utilise as silvicultural decision-making support tool in South African eucalypts plantations and suggest that it is worth exploring its capabilities.

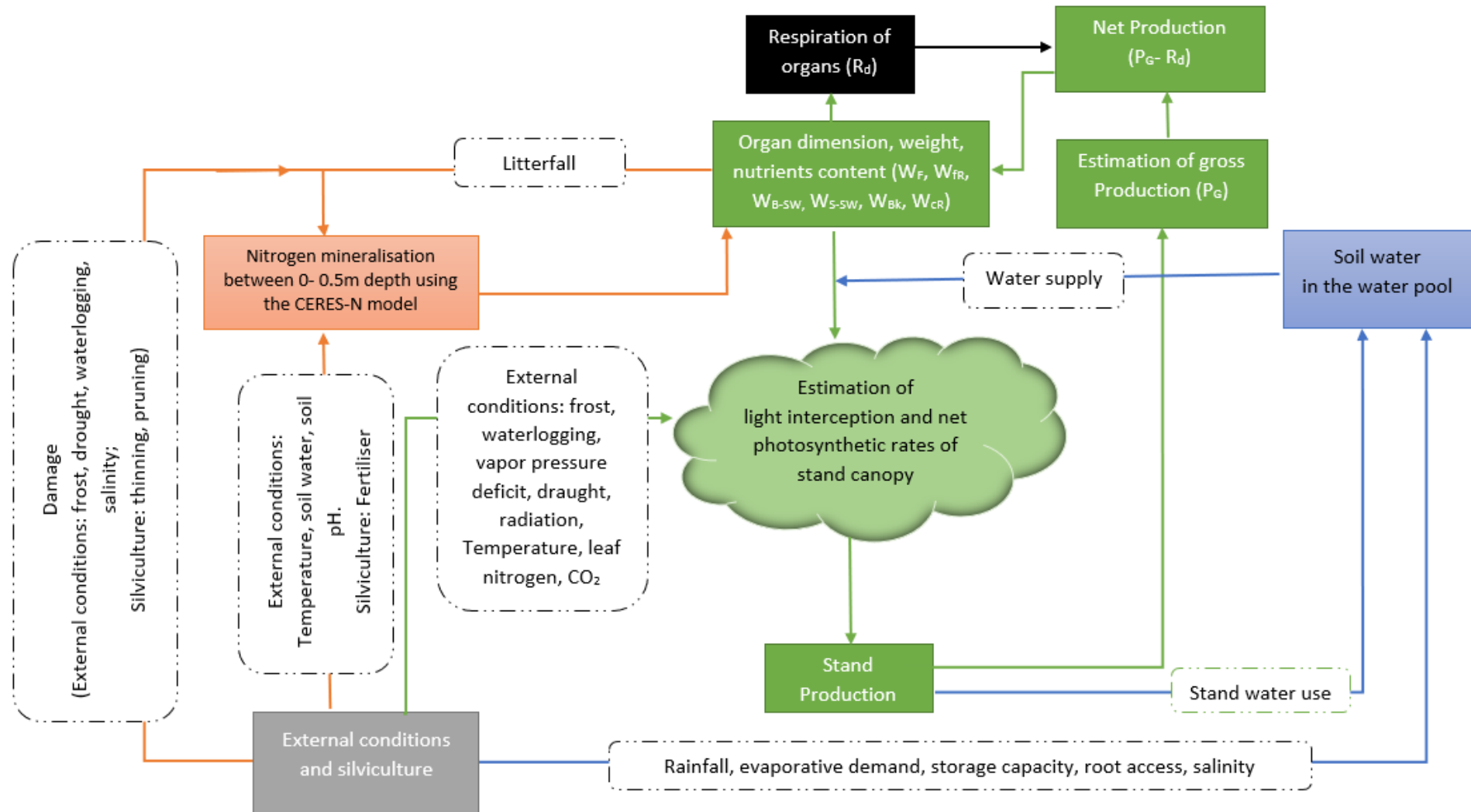


Figure 2.2: Simple flow diagram of major interactions in CABALA from Battaglia et. al. (2004), where W_F , W_{FR} , W_{B-SW} , W_{S-SW} , W_{Bk} , W_{cR} are foliage, fine roots, branch sapwood, stem sapwood, bark, coarse- roots, respectively.

2.2.1.2. *Tree biomass pool*

CABALA assumes that trees are identical within the stand and that the biomass pool comprises of nine active and passive functional compartments in total. The active functional compartments include foliage (W_F), branch sapwood (W_{B-SW}), stem sapwood (W_{S-SW}), coarse roots sapwood (W_{CR-SW}), and fine roots (W_{FR}) which are all associated with nutrient uptake and growth processes. The remaining compartments, namely bark (W_{BK}), stem heartwood (W_{S-HW}), branch heartwood (W_B) and coarse roots heartwood (W_{CR}) are considered passive functional compartments. Biomass compartments assume a constant carbon and nitrogen ratio and no translocation of nitrogen and carbon takes place between compartments until senescence. These assumptions do not apply to foliage due to inconsistent nitrogen concentrations caused by daily re-translocation rates.

2.2.1.3. *Tree geometry and stand geometry*

The geometry of trees is described by tree total height above ground, average crown length, root depth and the horizontal extent of crown and root systems in x and y intersecting planes. Branches are assumed to emerge from the stem at a constant angle with an average maximum branch length. Trees are positioned within and between blocks, which have a given spacing, and the orientation of blocks can vary. The canopy geometry is organised on a three-dimensional, rectangular, Cartesian xyz co-ordinate system with the z-axis vertical. The x and y-axis in ellipsoids represent the inter-row and intra-row respectively and are oriented arbitrarily due to symmetry. Hedgerows have an x- and y-axis normal to the hedgerow and along the hedgerow, respectively. The width of hedgerows is in the x-axis direction and length in the z-direction. Hedgerows are assumed to have an infinite length l in the y-direction. CABALA assumes that the canopy consists of constant leaf area density defined as the single-sided leaf area per unit volume in the canopy.

2.2.1.4. *Production and allocation*

- i. Light interception

The first estimate of light interception is calculated for an array of noninteracting ellipsoids, followed by a light interception for converging rows within nonintersecting hedgerows and finally a light interception estimate for when trees converge. The latter is estimated with the big-leaf model and the Beer-Lambert law (Ball, et al., 1987). The ellipsoids and hedgerow canopy light interception are calculated by estimating the flux intercepted by the canopy as function of accumulated incident radiation accumulated, leaf area and distance. This is followed by estimating the radiant energy intercepted by the canopy as an integral over all beams passing through shadow area of the canopy. The last step is the estimation of the fraction of radiation intercepted as a function of incident radiation by the canopy of number of crowns or hedgerows intercepted by the canopy, and number of crowns or hedgerows and fraction of each hectare planted.

ii. Photosynthesis

The net photosynthesis rate is estimated by means of a non-rectangular hyperbolic photosynthesis function defined in **Equation 2.1**, while the gross primary production is estimated like the model of Sands (1995).

$$A_{net} = A(Q) \left(\frac{C_i - \Gamma^*}{C_i + C^*} \right) - R_d$$

Equation 2.1

Where C_i is intercellular CO_2 , R_d is dark respiration rate, Γ^* and C^* are empirical parameters which are characteristic of the $A-C_i$ curve. $A(Q)$ is the photosynthetic light response and is given by a non-rectangular hyperbolic function of Q incident upon the leaf.

iii. Transpiration

CO_2 required by assimilation is supplied from the atmosphere to the leaf intercellular by means of diffusion across the boundary layer through the stomata. Stomatal conductance is estimated

with the Ball Berry empirical equation (Ball, et al., 1987); this value is converted to canopy conductance which is required to calculate demand evapotranspiration using the Penman-Monteith equation (Monteith, 1973). Canopy water use is assumed to be lower than the estimated atmospheric demand minus evaporation of crown stored water and maximum uptake evapotranspiration or the supplied limited rate determined by fine roots mass and relative available water.

iv. Respiration

Plant respiration is determined by means of the growth and maintenance respiration paradigm assuming a growth respiration of 0.25 into biomass and a maintenance respiration proportional to tissue nitrogen and sensitive to temperature. The respiration equation is described in Battaglia and Sands (1997). Foliage has a fixed lifespan of $1/y_F$ years in the absence of stress while branches are shed as the green crown rises. Fine roots and bark turnover rates Y_F and Y_{Bk} are user-defined constant proportions of stand biomass. Sapwood turnover to heartwood in stems and coarse roots occurs from the excess stand basal area over sapwood area required to sustain current leaf area. Self-thinning is as implemented by Sands and Landsberg (2002).

v. Carbon allocation

The carbon allocation strategy in CABALA is shown in **Figure 2.3**. Plant minimum growth rate depends on the supply of carbon (G_C), water (G_W) and nitrogen (G_N) which balance is achieved when $G_C = G_W = G_N$. This balance changes daily as environmental conditions change and the plant grows, thus the plants adjust active functional components to prevent imbalances.

G_C is estimated from P_G used to determine the target foliage and fine root biomass to bring each resource-limited growth rate into balance. Carbon is thereafter allocated such that the target biomass is met closely as possible. Growth is achieved when there is enough carbon allocation to passive functional tree components, and the below-to above ground ratio is achieved. To

maintain tree growth, the model aims to allocate carbon to foliage and fine roots as closely as possible to the target biomasses so that there is sufficient carbon allocated to passive functional tree components to meet the transport requirement by the pipe model, and the below-to above-ground biomass ratio is achieved.

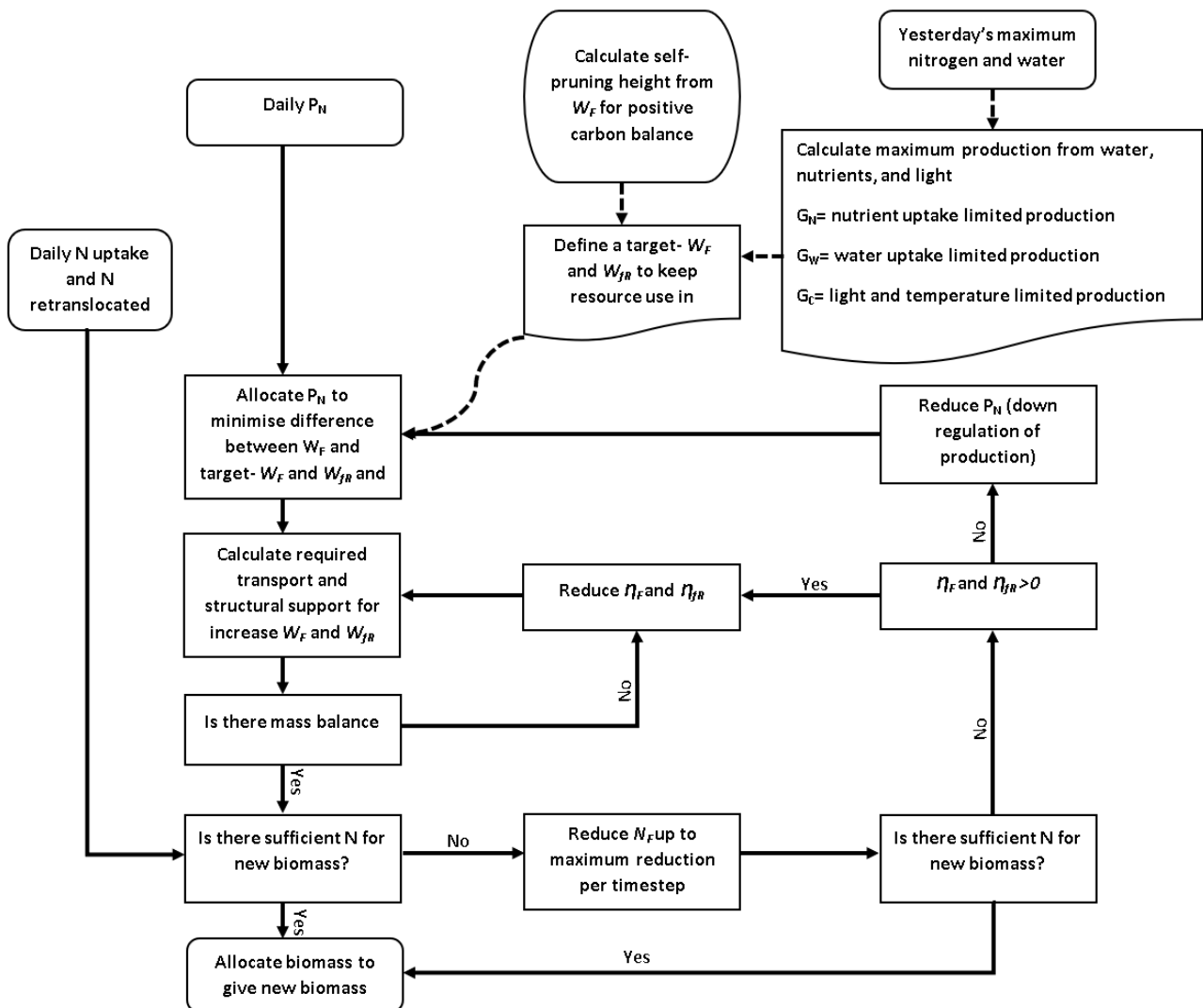


Figure 2.3: This diagram (from Battaglia et al., (2004)) represents the protocol applied in CABALA to allocate biomass to standing trees. The symbols P_N , η_F , η_{FR} , N and N_F represent net primary production, net primary production allocated to foliage, net primary production allocated to fine roots, nitrogen and folia nitrogen concentration respectively.

The water pool from which tree water-use is extracted from, is defined as the pool occupied by tree roots, the size of which increases as roots expand vertically and horizontally. Pre-dawn leaf water potential is calculated from this pool according to **Equation 2.2**. The estimated pre-dawn water potential is incorporated in the Ball and Berry (1990) model to estimate stomatal conductance required to estimate evapotranspiration as explained in **Section 2.2.1.4** item iii. G_w is therefore estimated as the product of maximum soil water uptake and water-use efficiency of the previous day.

$$\psi_{pd} = (\psi^+ - \psi^-) \times \left(1 - \left[\frac{1}{1 - e^{-b}} \right] (1 - e^{-b\theta}) \right) + \psi^-$$

Equation 2.2

Where ψ_{pd} (MPa) is pre-dawn leaf water potential, ψ^+ (MPa) is pre-dawn leaf water potential observed at $\theta=1$, ψ^{-1} (MPa) is pre-dawn leaf water potential observed at $\theta=0$, and b is the exponent of the moisture released according to Campbell and Norman (1998).

Nitrogen transformations are simulated for soils within the 0.5m soil depth using the CERES-N sub-model (Godwin & Jones, 1991). Nitrogen transformations simulated in the CERES-N model includes nitrogen mineralization and immobilization, nitrification, and de-nitrification and the simulation is done for a whole stand-soil system (Quemada & Cabrera, 1995). The available, labile nitrogen found within the 0.5m soil depth, is taken up with water and allocated to biomass pools fractionally at varying steps of 0.01. Nitrogen uptake must be sufficient to meet the new biomass demand. Insufficient nitrogen supply results to allocation of nitrogen to less demanding tissue and decrease daily net production should the nitrogen supply remain insufficient. The crown's specific leaf area is affected by foliage nitrogen content.

2.3.1. Strengths/weaknesses of the CABALA model

CABALA has been parameterized for *Eucalyptus globulus* (*E. globulus*), *Eucalyptus nitens* (*E. nitens*), *Eucalyptus polybractea* (*E. polybractea*), *Eucalyptus horistes* (*E. horistes*), *Eucalyptus kochii* (*E. kochii*) and *Pinus radiata* (*P. radiata*) (Battaglia, et al., 2007). Through these studies, certain weaknesses and strengths have emerged, summarised in **Table 2.3**. In general, the CABALA model's highly accurate volume prediction is owed to its complexity and high demand of accurate detailed site description data (Miehle, et al., 2009).

Table 2.3: A summary of the CABALA model's strengths and weaknesses.

Strengths	Weaknesses
Gives a high-volume prediction accuracy ($R^2=0.94$) in <i>E. globulus</i> stands in Southern Australian states (Miehle, et al., 2010).	Requiring high data input, thus limiting its applicability on sites with inadequate detailed soil data availability.
Suitable for silvicultural management decision in <i>E. globulus</i> plantations with detailed and accurate site data (Miehle, et al., 2009).	Tend to underestimate growth when approaching year 8 of harvest age (Miehle, et al., 2010).
Good simulation of canopy architecture as the model take the edge effect, tree spacing, and row orientation into account. (Mohammed, et al., 2003)	Tend to underestimate mortality in PSP's with high mortality rates caused by pests and hence over-predicting tree biomass on PSP (Pinkard, et al., 2014).

2.3.2. Applications of CABALA

The CABALA model was first parameterised for *E. globulus* and has been widely applied in Australian *E. globulus* plantations. In Northern Tasmania's *E. globulus* plantations, the model gave

a model efficiency, defined as the difference between predicted and observed values at each reference plot (Almeida, et al., 2010), of 0.94 for predicted vs observed volume in 15 sites (Battaglia, et al., 2004). Mummery and Battaglia (2004) further demonstrated how the model could be used to develop silvicultural prescriptions and management regimes to maintain production and reduce the risk of drought death in plantation.

Mohammed et.al. (2003) took advantage of the CABALA model's good canopy architecture model to predict the effect of 50% bottom-up defoliation of a 50-ha plantation on a high-quality site in Western Australia. CABALA was also used to calculate leaf wetness ("water-holding capacity" of the canopy) to better predict risk on site. CABALA had the highest model efficiency when Miehle et.al. (2009, 2010) compared the model with 3-PG, 3-PG+, Forest-DNDC, and MoBiLE-PTD and was found to be the most reliable for management decision tool. Drew et.al. (2010) demonstrated how CABALA outputs, using only parsimonious adjustments of some key parameters, could be used to run a xylem formation modelling system not only on *E. globulus*, but also *Eucalyptus grandis x urophylla*, *E. nitens*, and *Eucalyptus grandis x camadulensis*.

The CABALA model light interception and photosynthesis sub-models were enhanced to allow the assessment of foliage damage and defoliation by pests and to re-grow foliage in the canopy. An enhanced model was tested on pest damage or artificially mimicked pest damaged *E. grandis* and *E. nitens* plantations of southern Australia and the model prediction accuracy was $R^2 = 0.96$ and 0.97 for defoliation and non-defoliation stands respectively. Eyles et.al. (2013) further applied the enhanced CABALA model to assess the impact of pest defoliation and canopy foliage recovery after fertilising *E. globulus* stands in Northern Tasmania, whereby the model gave good results. CABALA gave a model efficiency of 0.93 for the comparison of observed and predicted volume for *P. radiata* stands in Northern Tasmania (Paul, et al., 2013). Pinkard et.al. (2014) used outputs from the CLIMEX model to develop defoliation scenarios in CABALA and applied CABALA output in FULLCAM model to determine carbon sequestered in living biomass.

2.3. Available data and parameters for testing CABALA in South African *Eucalyptus grandis* x *urophylla* plantations

2.4.1. Soil data

Process-based forest models, particularly CABALA, require detailed soil and weather data which is often not readily available in South African plantations. The available soil data that have information on soil include only soil form, clay percentage and soil texture over a soil depth of 1200-1500cm (close communication with Mondi Ltd and Sappi Ltd). These soil physical characteristics do not fulfil CABALA soil data requirements. The detailed soil information required by CABALA includes organic carbon percentage, C:N ratio and bulk density at different soil depths (0-10, 10-20, 20-50 cm) as well as soil texture of each soil horizon (Battaglia, et al., 2004); obtaining this data is time consuming and expensive.

2.4.2. Weather data

South Africa does not have access to extensive, widely available weather data sources such as those available through products like SILO (<https://researchdata.edu.au/silo-climate-database/969133>) in Australia. While CABALA can readily be run in Australia using these kinds of data, in South Africa the situation is more difficult. Long-term mean gridded datasets are available, but this is not able to take account of periodic droughts. Many gridded datasets National Aeronautics and Space Administration are very coarse (Gupta, et al., 2020). Therefore, for the right level of granularity in modelling, it is necessary to rely on daily weather data from the nearest South African weather stations to the compartment/s of interest. These frequently lack radiation data and sometimes have missing rainfall or other data. Interpolated daily weather data using interpolation approaches (e.g. the meteoland R package (<https://cran.r->

project.org/web/packages/meteoland/vignettes/UserGuide.html) can be used but these interpolated daily weather data do not necessary represent the whole landscape.

2.4.3. Parameters for GU

A number of studies have aimed to parameterise process-based growth models for GU Although not focussing on CABALA specifically, many of the parameters are quite generic/portable and applicable or adaptable to CABALA. Those which were considered in this thesis are summarised in **Table 2.4**. The most applicable CABALA parameter to which these numbers can be assigned is also given.

Table 2.4: Published physiological parameters for *Eucalyptus grandis* x *urophylla* hybrids.

Parameter	Meaning	Units	Value	Author
Single leaf light response				
T_{opt}^*	Optimum temperature for photosynthesis	$^{\circ}\text{C}$	25	Stape et al., (2004)
				Marsden et. al., (2012)
θ	Shape of single- leaf light response curve	-	0.95	Forestal et al., (2013)
				Marsden et. al., (2012)
Γ^*	Photosynthetic CO ₂ compensation point	Pa	56.25	Bernacchi et al., (2001)
			49.41	Marsden et. al., (2012)
Parameters for foliar respiration				
r_{a0}	Value of foliar respiration at temperature $T = T_0$	mmol CO ₂ , m ⁻² leaf s ⁻¹	1	Bernacchi et al., (2001)
			0.7	Ryan et al., (2009)
			1.28	Marsden et. al., (2012)
Single leaf and canopy conductance parameters				
g_0	Minimum stomatal conductance	mol H ₂ O m ⁻² ground s ⁻¹	0.36	Forestal et al., (2013)
			0.2	Valadares et al., (2014)
f_{d1}	Multiplier in D: g_s relationship	-	0.81	Morris et al., (2004)
f_{d2}	Exponent in D: g_s relationship	kPa ⁻¹	0.86	Morris et al., (2004)
			1.09	Kelly et al., (2013)
f_{y1}	Multiplier in soil water potential: g_s relationship		0.52	Mielke et al., (1999)
f_{y2}	Exponent in soil water potential: g_s relationship	MPa ⁻¹	-0.96	Mielke et al., (1999)
f_{y3}	Number of days today's water stress influence conductance	Days	8	Battaglia et al., (2004)
r_{Q-C}	Fraction of reflection that is reflected by crown	-	0.3	Battaglia et al., (2004)
Rainfall interception model				
I_L	Scalar between leaf area index and interception	kg H ₂ O m ⁻² leaf	0.3	Marsden et. al., (2012)
Nitrogen effects in photosynthesis and specific leaf area				
k_N	Attenuation of N through canopy with cumulative L	m ² ground m ⁻² leaf	0.5	Stape et al., (2004)
Tissue nitrogen parameters				

N_{fr}	Average fine root nitrogen concentration	kg N kg ⁻¹ DM	0.55	Marsden et. al., (2012)
α	Fraction of nitrogen re- translocated from tissues on senescence	kg N kg ⁻¹ DM	0.435	Marsden et. al., (2012)
<i>Allometrics and stand architecture</i>				
β_{w3L1}	Multiplier in relationship between stem sapwood cross-sectional area and L	-	0.96	Zhu et al., (2015)
β_{w3L2}	Exponent in relationship between stem sapwood cross-sectional area and tree height	-	0.8	Zhu et al., (2015)
β_{w3L3}	Exponent in relationship between stem sapwood cross-sectional area and L	-	0.37	Zhu et al., (2015)
<i>For N driven respiration</i>				
r_c	Construction respiration ration	-	0.1	Ryan et al., (2009)
Q_{10}	Q ₁₀ for respiration	-	1.3	Ryan et al., (2009)

MATERIALS AND METHODS

3.1. Introduction

Sands (2004) proposed that five classes of data can be used to develop model parameter sets for process-based models (PB): biomass harvest, field data, literature, and mensuration and physiological data. In this thesis, these types of data were generated with the objective of creating a parameter set suitable for use in the CABALA model for predicting growth of the South African *Eucalyptus grandis x urophylla* hybrid (GU) resource. To exhaustively test and develop a completely robust parameter set is a prohibitively expensive, time-consuming exercise, however, and in this thesis, it was not possible to exhaustively re-evaluate or sensitivity test the full set of CABALA parameters.

3.2. Fieldwork

3.2.1. Study sites and species

Field work was conducted on a set of 18 managed forest compartments growing clonal GU situated on the coastal plain of the east coast of northern KwaZulu- Natal (KZN), South Africa, hereafter called “Zululand” (

Figure 3.1). The region is relatively flat with a mean elevation of 47 m above sea level. Zululand experiences a subtropical climate (du Toit, et al., 2001) with a mean precipitation of 1121 mm and a mean temperature of 22 °C (**Table 3.1**). Nonetheless, the rainfall is quite variable, with periodic droughts, and exhibits a strong gradient, increasing towards the coast, and from north to south along the coast (du Plessis & Zwolinski, 2012).

The soils of the Zululand coastal area have a distinctive sandy texture and are the result of from aeolian sand deposition (Smith & du Toit, 2005). These soils are reported to have a depth of at least

30 m with free drainage (Dovey, et al., 2011). Orange mottles are sometimes present below 100 cm soil depth in this region (Smith & du Toit, 2005) and were reported by Smith & du Toit (2005) as an indication of the presence of water table in some areas (Smith & du Toit, 2005). A detailed description of the protocol used to sample soils from the study sites are given in *Section 3.2.3*.

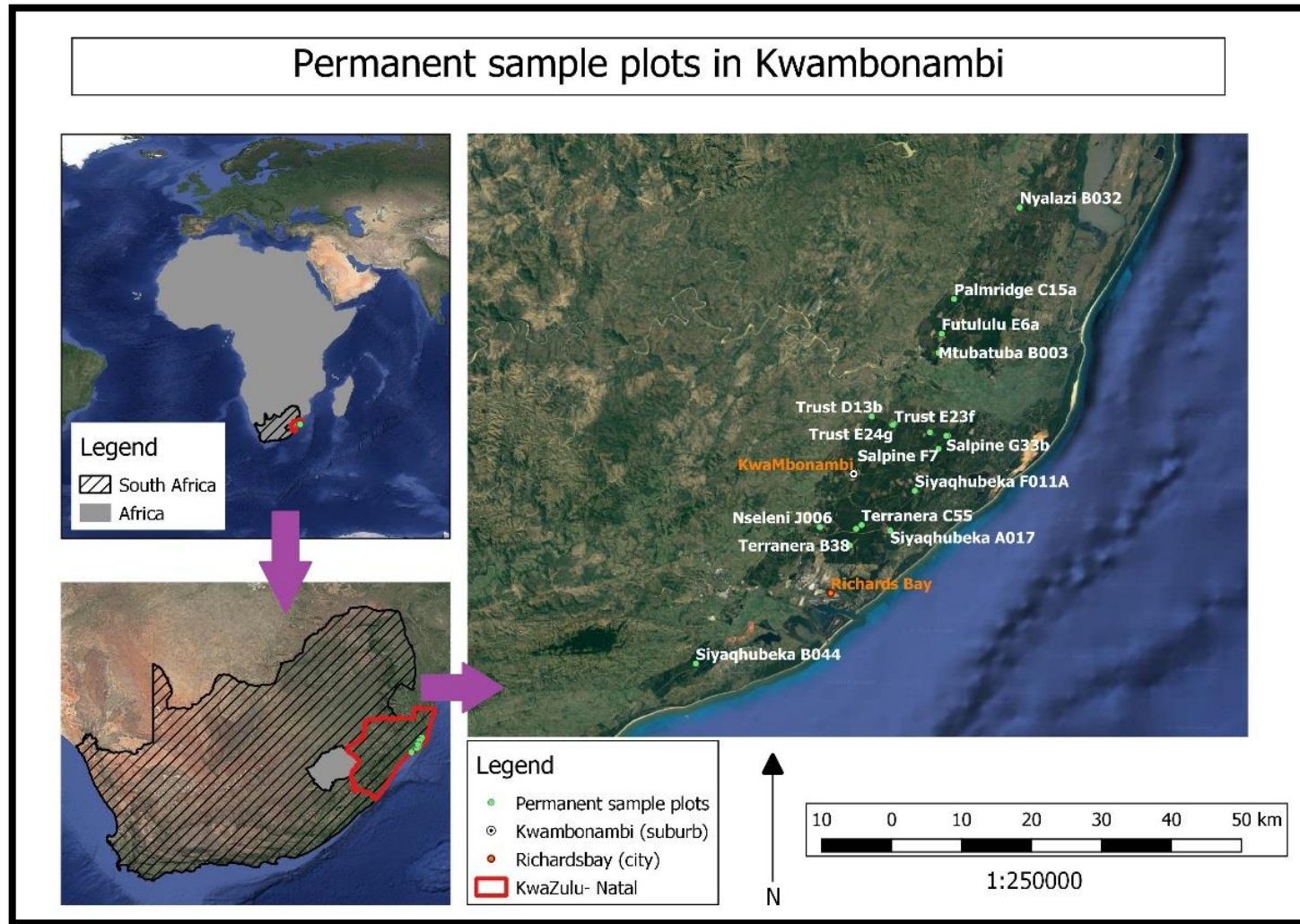


Figure 3.1: A map of the locations of the 18 study sites (all with permanent sample plots) in the eastern coastal plain of KwaZulu-Natal (Zululand).

Table 3.1: Site description of the study sites, with compartment numbers as allocated by the two forestry companies. The abbreviation a.s.l is for above sea level, MAT for mean annual temperature, and MAP for mean annual precipitation).

Company	Compartment number	Longitude	Latitude	Altitude (m a.s.l)	MAT (°C)	MAP (mm)	Soil form	Nominal Soil depth (cm)	Soil texture
Sappi Ltd.	Trust D13b	32,12	-28,51	49	21,80	913,83	Fw	1201	fi-meSa
Mondi Ltd.	Nyalazi B032	32,33	-28,21	25	22,00	918,00	Cv21	1200	sa
Mondi Ltd.	Mtubatuba B003	32,21	-28,42	60	22,00	878,00	Fw1210	1510	mesa
Sappi Ltd.	Futululu E6a	32,22	-28,39	69	21,80	913,83	Fw	1201	fi-meSa
Sappi Ltd.	Palmridge C15a	32,24	-28,34	58	21,80	913,83	Fw	1201	fi-meSa
Sappi Ltd.	Salpine F7	32,21	-28,56	50	21,40	1165,10	Fw	1201	meSa
Sappi Ltd.	Mavuya B3a	32,2	-28,54	39	21,70	1081,80	Fw	1201	meSa
Sappi Ltd.	Trust E23f	32,15	-28,52	43	21,70	1081,80	Fw	1201	meSa
Sappi Ltd.	Terranera B38	32,1	-28,67	62	21,40	1191,44	Fw	1201	meSa
Sappi Ltd.	Trust E24g	32,15	-28,53	44	21,70	1081,80	Fw	1201	meSa
Sappi Ltd.	Salpine G22b	32,23	-28,54	20	21,40	1165,10	Fw	1201	meSa
Sappi Ltd.	Salpine G33b	32,23	-28,54	20	21,40	1165,10	Fw	1201	meSa
Sappi Ltd.	South Areas B35b	32,09	-28,68	60	21,40	1165,10	Fw	1201	meSa
Sappi Ltd.	Terranera C55	32,08	-28,7	40	21,40	1191,44	Fw	1201	meSa
Mondi Ltd.	Nseleni J006	32,04	-28,68	40	21,60	1088,00	Hu2200	1510	me-lmSa
Mondi Ltd.	Siyaqhubeka F011A	32,18	-28,62	65	21,50	1381,00	Ct2100	1510	meSa
Mondi Ltd.	Siyaqhubeka A017	32,14	-28,68	40	21,50	1420,00	Vf2110	1510	meSa

Mondi Ltd.	Siyaqhubeka B044	31,94	-28,67	60	21,50	1460,00	Hu2100	1510	me-lmSa
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3.2.1.1. “Marie-Curie CFF” compartments

Prior to the start of the research reported in this thesis a set of six compartments, referred to from here on as the so-called “Marie-Curie CFF” compartments, were established as part of a previous Marie-Curie Climate-Fit Forests (CFF) research project funded by the Marie-Curie International Research Staff Exchange Scheme (IRSES) programme of the European Union. Sappi (Ltd), Mondi (Ltd) and Stellenbosch University were amongst South African organisations which partnered with the Marie-Curie IRSES programme (<http://www.climatefitforests.eu/index.php>). The objectives of that prior study were to understand short-term growth variability in younger/older stands at varied levels of drought. To achieve this, a set of dendrometer bands were installed in December 2013. By the time field work for the present study was undertaken in 2018, one of the original six sites had been felled. Five remained (**Table 3.2**), and these sites became primary points of focus for this study and were used as a subset of sites (from the total of 18) at which a particularly extensive sampling campaign was undertaken.

These “Marie-Curie CFF” compartments were designed to represent relatively “wet”, “moderate,” and “dry” sites with mean annual precipitation <1000 mm, 1000-1100 mm and >1100 mm, respectively. Trees were planted either with a spacing of 3.0 m x 2.5 m or 3.0 m x 2.2 m and received 60 kg/ha LAN (28) fertiliser at planting date. The LAN (28) is a granular form fertiliser that has a 50:50 ratio of ammonium-N and nitrate-N which makes a total of 28 % of the LAN (28) fertiliser (<https://products.sasol.com/pic/products/home/grades/ZA/5lan/index.html>). Furthermore, no weeding, pruning or thinning treatments were applied on these sites. “Marie-Curie CFF” compartments consisted of rectangular permanent sample plots with 100 trees per plot (10 x 10 trees) of an area ranging between 0.066- 0.075 ha.

Table 3.2: Site establishment summary of “Marie-Curie CFF” compartments where TPH_0 is stand density at establishment date and MAP is mean annual precipitation.

Company	Compartment	Establishment. date	Age₂₀₁₈ (years)	Clone	Spacing (m x m)	TPH_0 (tree/ha)	Plot Area (ha)	Initial Trees in plot	MAP range(mm)
Sappi Ltd.	Trust D13b	2011/05/16	6	GU W1830	3.0 x 2.2	1515	0,066	100	<1000
Sappi Ltd.	Trust E23f	2012/06/16	6,75	GU W1700	3.0 x 2.5	1333	0,075	100	1000-1100
Sappi Ltd.	Trust E24g	2008/03/15	7,8	GU MIXED	3.0 x 2.2	1515	0,066	100	1000-1100
Sappi Ltd.	Salpine G22b	2008/04/15	5,8	GU W1022	3.0 x 2.2	1515	0,066	100	>1100
Sappi Ltd.	Salpine G33b	2011/03/16	8	GU W1022	3.0 x 2.5	1333	0,075	100	>1100

3.2.1.2. Kwambonambi Compartments

Of the remaining 13 sites used in study reported in this thesis (*Table 3.3*), seven were managed by Mondi (Ltd), while Sappi (Ltd) managed the remaining six sites. Mondi-managed compartments were established with a spacing of 3.0 m x 2.5 m/ 3.0 m x 2.2 m and received a 60 kg/ha LAN (28) fertiliser treatment at establishment date. Sappi-managed compartments were established with spacings of 3.0 m x 2.5 m /3.0 m x2.2 m /2.7 x2.4 m and received 60 kg/ha LAN (28) fertiliser treatment at establishment date. No pruning, thinning, nor weeding treatments were applied at any of the 13 compartments during their rotation period.

At all 13 sites, the permanent sample plots were rectangular, using 8 X 8 trees on Mondi (Ltd) sites and 9 X 9 trees on Sappi (Ltd) sites. Across the sites with different spacing, sizes (area basis) of plots also varied. There were no dendrometers installed at these sites, however, diameter at breast height and tree height were measured on all trees in each permanent sample plot every one or two years during their rotation growth period. Data from these PSPs were used to create an allometric parameter set for GU hybrid and to test the model performance in Zululand.

Table 3.3: Site establishment summary of Kwambonambi compartments where Age₂₀₁₈ is the age of stand in year 2018, TPH₀ is stand density at establishment date.

Company	Compartment	Establishment date	Age ₂₀₁₈ (years)	Clone	Spacing (m x m)	TPH ₀ (tree/ha)	Plot Area (ha)	Initial Trees in plot
Mondi Ltd.	Nyalazi B032	2012/08/01	7,8	GGRAURO	3.0 x 2.5	1326	0,048	64
Mondi Ltd.	Mtubatuba B003	2011/07/04	6,9	GGRAURO	3.0 x 2.5	1336	0,048	64
Sappi Ltd.	Futululu E6a	2010/08/15	5,58	GU W1830	3.0 x 2.5	1333	0,061	81
Sappi Ltd.	Palmridge C15a	2010/06/16	7,4	GU W1700	3.0 x 2.2	1515	0,053	81
Sappi Ltd.	Salpine F7	2010/11/16	8	GU W1830	3.0 x 2.2	1515	0,053	81
Sappi Ltd.	Mavuya B3a	2010/04/16	6,67	GU W1700	3.0 x 2.5	1333	0,061	81
Sappi Ltd.	Terranera B38	2011/03/16	7,1	GU W1830	3.0 x 2.2	1515	0,053	81
Mondi Ltd..	Siyaqhubeka B044	2011/06/01	10,1	GGRAURO	3.0 x 2.5	1280	0,050	64
Sappi Ltd.	South Areas B35b	2012/04/16	10	GU SGU1932	2.7 x 2.2	1684	0,048	81
Sappi Ltd.	Terranera C55	2010/06/16	5,67	GU SGU1932	3.0 x 2.5	1333	0,061	81
Mondi Ltd.	Nseleni J006	2010/07/01	7,7	GGRAURO	3.0 x 2.2	1479	0,043	64
Mondi Ltd.	Siyaqhubeka F011A	2012/08/02	7,75	GGRAURO	3.0 x 2.5	1314	0,049	64
Mondi Ltd.	Siyaqhubeka A017	2011/07/01	7,1	GGRAURO	3.0 x 2.5	1366	0,049	64

3.2.2. Above- ground biomass harvesting and main measurements

In July 2018, a major campaign was undertaken in which a full set of DBH and height measurements were made at all sites, and soil samples were taken at the same time. In addition, biomass harvests were done at the five “Marie-Curie CFF” compartments.

3.2.2.1. Harvesting

Above- ground biomass was collected for measurements from the five “Marie-Curie CFF” compartments ranging from six to ten years of age and were classified into “wet”, “moderate”, and “dry” sites based on their mean annual precipitation. Three trees representing the first quartile (Q1), third quartile (Q2) and maximum of the diameter frequency distribution of stand were harvested in each compartment.

Tree total lengths, including stump height, were measured with a measuring tape after tree felling. The tree crown length, assumed to start from the tip of the crown down to the last living branch at the bottom of the crown, was recorded and divided into five equal sections that were numbered from the tip of the live crown to the bottom *Figure 3.2*.

Branch diameter at 40mm from the trunk was measured with calipers on the last branch of each section, counting from the live- crown tip to the base, of the selected tree to represent the maximum diameter tree in the diameter frequency distribution of each plot. The length of the same branches was measured with the same measurement tape and recorded in respect of their diameter. The angle between the stem and branch was measured with a protractor. Measurements done on selected trees are illustrated in *Figure 3.2* .

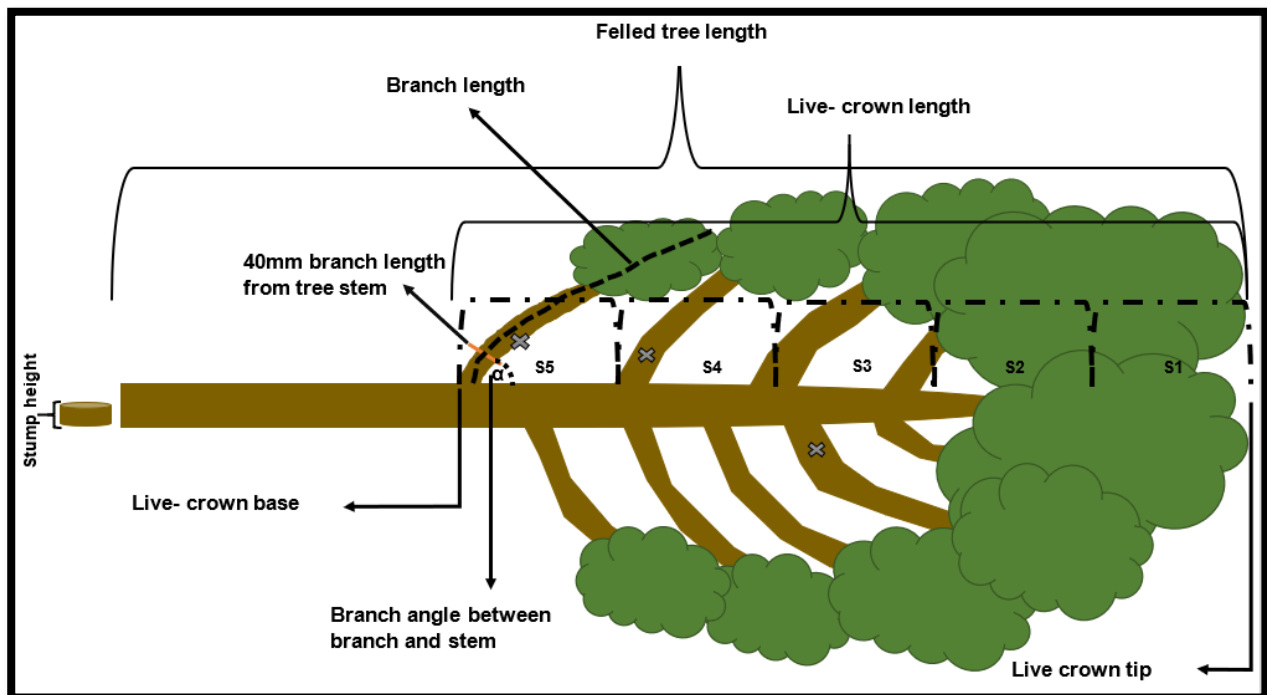


Figure 3.2: A schematic representation of a felled tree. Total tree length is the sum of the stump height and tree length. The living crown 5 sections (S1- S5) from the base of the living crown to the tip are represented by spaced lined brackets. The last branch falling fully inside of its respective section was marked. Branch measurements (branch total length and branch angle) are illustrated in section 5 (S5) of the living crown: the orange shaded line on the shaded x branch represents the branch length from which branch angle (α) was measured.

All foliage was stripped from each section of the tree and fresh weight recorded on sites using a portable 50 kg scale with an accuracy of 200 g. A well-mixed sub- sample of leaves for water content determination was sampled for each living crown section followed by recording the fresh weight. A second sub- sample was sampled for specific leaf area determination and 30-45 healthy leaves were selected from the sub- samples followed by recording the fresh weight of the subsample. Sub-samples were placed in sealable plastic bags and labelled according to the compartment, tree number and canopy section.

A set of 2 cm thick discs were sampled to determine water content, wood density, and bark to wood ratio of wood (**Figure 3.3**, category A) at @ 1.3 m (breast height) and 20 %, 40 %, 60 % and 80 %

of tree height. A second set was sampled to determine the sapwood area. (**Figure 3.3**, category B) at 1.3 m and at the lowest live branch section of the trunk.

After above- ground biomass sampling, the tree trunk fresh mass was measured on a hanging 100 kg (± 0.5 kg) scale using a suspended net. The mass of branches of all sections combined was measured and recorded in the same manner as the tree trunk. Thereafter, a sub-sample of branches were cut with a branch scissors arbitrarily, placed in sealed bags and labelled according to their compartment.

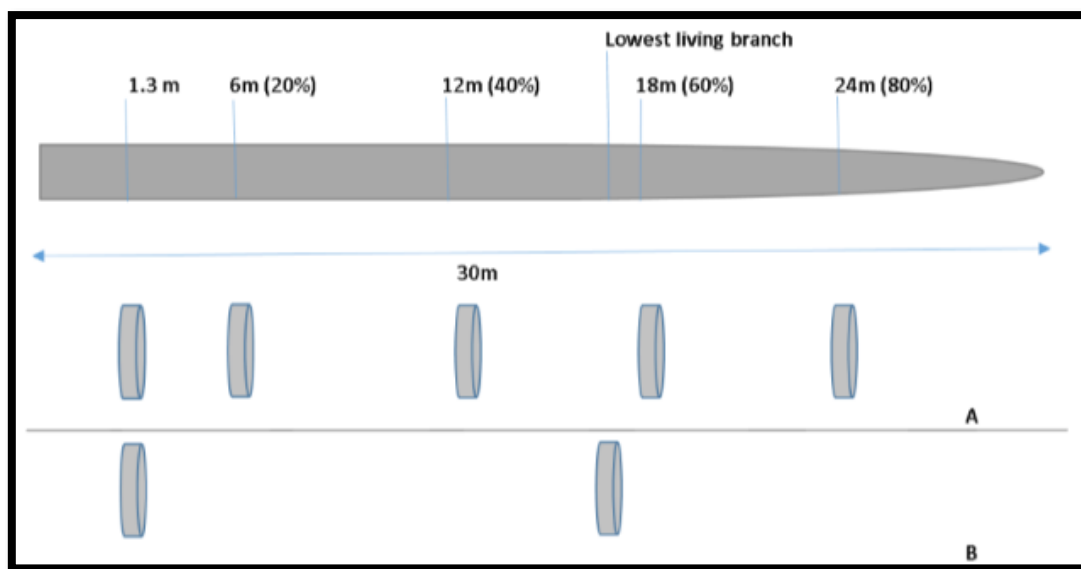


Figure 3.3: A schematic representation of discs sampled from logs. Discs in the A category were sampled for determining water content and bark: wood ration. Discs in the B category were sampled to determine the sapwood area.

All fresh biomass collected and inserted in sealed plastic bags were stored in cooler boxes with ice during collection and travelling. Collected fresh biomass was stored in the refrigerator during our campaign in Zululand.

3.2.2.2. Laboratory

Fresh leaf sub- samples with 30- 45 healthy leaves per sub- sample were selected for determining leaf area from every tree harvested in the “Marie-Curie CFF” compartments. These were scanned

on a LI-COR 1000 leaf area scanner (LI-COR, Inc.), followed by oven drying at 65 °C until constant dry leaf mass was reached, typically after 19 to 22 days. Specific leaf area (SLA) was estimated according to **Equation 3.1** for each full sample:

$$SLA (cm g^{-1}) = \frac{Total\ leaf\ area\ (cm)}{Dry\ leaf\ mass\ (g)}$$

Equation 3.1

Leaf sub-samples that were sampled for determining water content were oven dried at 65 °C until constant dry leaf mass was reached; discs samples at 20 %, 40 %, 60 % and 80 % of tree trunk length, and sampled branches were oven dried at 105 °C until constant dry leaf mass was reached.

The water contents of these biomass were estimated according to **Equation 3.2**:

$$Water\ content\ (\%) = \frac{Fresh\ biomass\ mass\ (g) - Dry\ biomass\ mass(g)}{Fresh\ biomass\ mass(g)} \times 100$$

Equation 3.2

The water content % of biomass was used to determine the dry mass of the full fresh samples measured on sampled trees by subtracting the water content % of biomass from the total fresh mass of its respective biomass type (leaves, branches and stem)

The density of wood and branches were estimated from sampled discs and branches according to

Equation 3.3:

$$Biomass\ density = \frac{Dry\ biomass\ mass\ (kg)}{Fresh\ biomass\ mass\ (kg)}$$

Equation 3.3

The bark was removed from each dry disc sample followed by oven drying each disc with its respective lose bark at 65 °C until dry constant mass was reached. Wood bark percentage was estimated according to **Equation 3.4**:

$$\text{Bark (\%)} = \frac{\text{Dry disc mass with bark (g)} - \text{Dry disc bark mass(g)}}{\text{Dry disc mass with bark (g)}} \times 100$$

Equation 3.4

Photographs were taken of fresh discs sampled at 1.3 m and below the lowest living branch of living crown to determine sapwood area. The images were processed using ImageJ image analysis (Image J, version 1.52) software and the prominent sapwood was traced, and the area calculated. Most disc samples from the lowest living branch did not have prominent heartwood, this implied that those discs only had sapwood.

3.2.3. Soil sampling

3.2.3.1. Soil sampling

CABALA required inputs of soil chemical (soil nitrogen content, carbon content, and pH) and physical properties (soil texture and bulk density) from all 18 sites. Soil texture was used to estimate initial soil water content of the soil profile and hydraulic conductivity related activities using soil property parameters by Campbell & Norman (1998).

Before starting with soil sampling, the center of each permanent plot was located, and pits were marked according to **Figure 3.4**. Excess debris was removed gently from the soil surface before coring into soil pits. The first soil pit coring was for soil textural analysis. This was done by coring the middle pit (the grey pit in the middle of **Figure 3.4**) with a 1.2 m manual steel auger at 10 cm intervals till 1.2 m soil depth was reached.

Soil contamination was avoided by removing excess soil at the top of the coring section of the auger. Sometimes the soil would be too sandy and when the auger is pulled from the cored sand, some of the sand in the auger would fall out from the auger head and about 5 cm soil auger head height would remain in the auger. The soil that fell out of the auger head was considered

contaminated was therefore not included in samples resulting in other samples having soil depths of, for example, 15 cm.

The soil was laid on plastic sheets after every 10 cm coring; consequent soils possessing a constant color over the soil depth gradient were grouped together. Soil was sampled from each grouped soil along the 1.2 m soil depth, inserted into plastic bags and labeled according to the compartments permanent sample plot, soil depth, and type of analysis for later analysis in the laboratory.

Soil samples for chemical analysis were taken from three pits which each was 2 m away from the 1.2 m soil texture analysis coring (see the dark orange pits in **Figure 3.4**). Soil pits were cored at 0-10 cm, 10-20 cm, and 20-50 cm soil depth with an auger. These three soil depths were selected because CABALA estimates nitrogen mineralization and soil evaporation over three surface soil layers (0-10 cm, 10-20 cm, and 20-50 cm soil depth). Soils were grouped according to their soil depth, mixed thoroughly, sampled, inserted into a plastic bag, and labeled according to the compartments' permanent sample plot, soil depth and their analysis in the laboratory.

The third sample was for bulk density determination and was taken 1 m away from the 1.2 m soil textural analysis core (see the yellow pit in **Figure 3.4**). Soil samples were taken at 0-10 cm, 10-20 cm, and 20-50 cm soil depths (for the same reason stated in the previous paragraph) by pressing a steel ring with a diameter of 7.5 cm and height of 6.5 cm into undisturbed soil. Each sample was inserted into a plastic bag and labelled according to the compartments' permanent sample plot soil depth. Precaution was taken to avoid disturbing the soil during the process of sampling the soil.

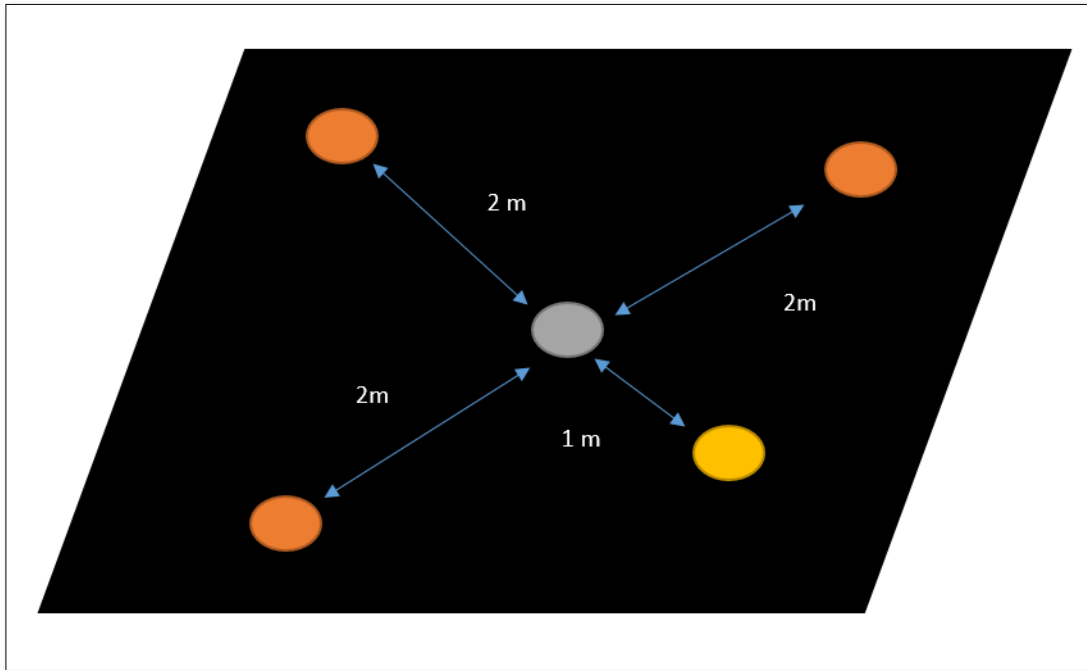


Figure 3.4: A schematic representation of soil pits for soil sampling. The middle grey circle represents the soil pit to be cored till 1.2 cm depth for texture analysis; the three orange circles represents the soil pits to be cored at three soil depth level (0-10cm, 10-20cm, 20-50cm) each for chemical analysis; and the yellow circle represents the pit to be core at three soil depths levels (0-10cm, 10-20cm, 20-50cm) for bulk density.

3.2.3.2. Laboratory

i. Soil texture and chemical analysis

Soil texture and chemical analysis soil samples were sent to the analytical labs at the Institute for Commercial Forest Research (ICFR) (<https://www.icfr.ukzn.ac.za>) in Pietermaritzburg to determine soil texture, pH, carbon-, and nitrogen content (**Table 3.4**). The ICFR determined soil particles sizes for soil texture, total carbon, and nitrogen content (%) with the Dumas method and Soil pH (H₂O and KCl).

Table 3.4: A table showing codes and description for soil analysis done by the Institute for Commercial Forestry Research for this study (ICFR). The codes are according to ICFR.

Code	Description
SA1	pH (H ₂ O and KCl),
SA3	Total carbon, nitrogen, and sulphur (Dumas method)
SA4	Particle size analysis

ii. Bulk density

Soil sampled for determining bulk density were transferred from their plastic bags into metallic containers (**Figure 3.5**) and dried at 105 °C till constant weight was reached. The metallic containers had an average weight of 16.50 g (standard error= 0.03) without soil. The coring cylinder's volume was known precisely to have a height of 6.7cm, diameter of 7.5 and an average weight of 173.99 g (standard error= 0.416). Bulk density was determined as the ratio of dry soil (grams) to the cylinder volume (cm³). There were no coarse roots or rocks present in the soil.



Figure 3.5: An example of bulk density soil samples in metallic containers.

3.2.4. Diameter at breast height and height

In July/August 2018, when all sites were visited, a final measure of DBH and height were made at all 18 sites primarily to get a consistent set of numbers for comparing to “end of rotation” CABALA estimated stand diameter at breast height (DBH), height and volume output with the observed stand DBH, height and volume. Tree height was measured with a transponder T3 and Vertex IV (Haglöf Sweden); no height measurement was done when it was windy. The DBH was measured with a measuring tape at breast height, at positions already marked on trees in the permanent sample plots (PSPs).

In addition to this data, prior measurements from PSPs were also available for our analysis. DBH and height was measured annually in all trees present in Sappi (Ltd) managed compartments’ permanent sample plots from the year 2012 up to 2018. Sites Futululu E6a and Salpine F7 lacked DBH and height data for 2014. Trees with dendrometer bands on the “Marie-Curie CFF” compartments’ plot had their dendrometer readings and tree height recorded every second week from November 2013 to August 2018.

Mondi-managed compartments’ PSP DBH and height measurements were between the years 2010-2013 up to 2018. DBH and height measurements were made for all trees present in the permanent sample plots. At least one year’s DBH and height data was available for these permanent sample plots with an exception for Mtubatuba B003 which had a complete data set from 2013- 2018. This long-term data set was made available by Mondi (Ltd).

An inventory summary was prepared for “Marie-Curie CFF” and Kwambonambi compartments using equations in **Table 3.5**. Dominant height was only estimated for the long-term data from Sappi (Ltd) and Mondi (Ltd) which height were only measured for a sample of trees in each PSP.

Table 3.5: Equations used to prepare inventory summary at stand level.

Equation No.	Estimate	Formula	Units	Abbreviation
1	DBH_{mean}	$\frac{\sum DBH}{\sum n}$	cm	DBH_{mean} = mean DBH of stand DBH =Diameter at breast height; n = number of trees
2	DBH_q	$\sqrt{\frac{\sum DBH^2}{\sum n}}$	cm	DBH_q = Quadratic diameter at breast height
3	H_D	$\frac{\sum_{i=1}^{20\%} Ht}{\sum_{i=1}^{20\%} n}$	m	H_D = Dominant height of 20% tallest trees Ht = Measured height
4	H_m	$\frac{\sum Ht}{\sum n}$	m	H_m = Mean height
5	A_{plot}	$\frac{esp_w * esp_l}{100}$	ha	A_{plot} = Plot area; esp_w = espacement width; esp_l = espacement length
6	$TPH0$	$\frac{\sum n}{A_{plot}}$	Trees per hectares	$TPH0$ = Trees per hectare at establishment
7	$TPH1$	$\frac{n_{obs}}{A_{plot}}$	Trees per hectares	$TPH1$ = Trees per hectare at 2018 enumeration; n_{obs} = observed trees
8	BA	$\frac{\pi * DBH^2 * TPH1}{40000}$	cm ² per hectares	BA = Basal area
9	$Volume$	$BA * H_m * f$	m ³ /ha	$Volume$ = Utilised volume. f = factor of 0.365 by (Kassier, 2012)

3.2.5. Leaf Area Index (LAI)

Leaf area index (LAI) is an important variable in process-based models (PBMs), and certainly in CABALA as this variable integrates conductance and photosynthesis across the canopy. It was important to characterise this value, at least for a sub-set of sites. Three methods were used for this study: estimates from destructive harvesting at the five “Marie-Curie CFF” sites, indirect measurement using a AccuPAR LP-80 Ceptometer and estimates from MODIS remotely sensed data.

3.2.5.1. Destructive Leaf Area Index measurements

Leaf area Index LAI ($\text{m}^2 \text{m}^{-2}$) was estimated using data from individual trees harvested at the “Marie-Curie CFF” compartments in mid-2018. Estimation of specific leaf area and weight of tree total dry leaves (W_{fd}) was described in *Section 3.2.2.2*. The mean leaf area (A_f) estimated according to *Equation 3.5*, of all three trees harvested in a permanent sample plots and their compartment estimated TPH₁ in *Section 3.2.4.2* was used to estimate leaf area index (*Equation 3.6*) of compartments.

$$A_f(\text{m}^2) = SLA(\text{m}^2 \text{kg}^{-1}) * W_{fd}(\text{kg})$$

Equation 3.5

$$LAI (\text{m}^2 \text{m}^{-2}) = \frac{A_f(\text{m}^2) * TPH1(\text{tree per ha})}{10\,000}$$

Equation 3.6

3.2.5.2. Non- destructive Leaf area index using a ceptometer

LAI was also recorded at all compartments using a AccuPAR LP-80 Ceptometer. An initial reading was taken outside the compartment in an open area that was not shaded by trees or any other obstacle. Immediately thereafter, a set of six measurements were taken, facing in the same direction, in the

permanent sample plot where the study trees were growing. Finally, three more readings were taken outside the compartment from the same location as the initial readings. These readings were stored after completing each plot. A final estimate of LAI was computed as a function of the leaf angle distribution parameter X , and above and below canopy readings of PAR. These readings could not, unfortunately, always be taken at the same time of day which introduces a certain amount of error between sites such as the underestimation of LAI in lower light intensity (Pokovai & Fodor, 2019). The ceptometer LAI was therefore corrected according to the methodology proposed by Lopes et al (2016). Bias was determined as the difference between the reference LAI estimated according to **Equation 3.6** (LAI_{ref}) and the observed LAI measured using the LP-80 ceptometer LAI_{obs}) at the “Marie-Curie CFF” compartments (see **Equation 3.7**). Bias and the basal area (B) were put in a regression equation to produce **Equation 3.8**. Bias was estimated for both “Marie Curie CFF” and Kwambonambi compartments using **Equation 3.8**; the estimated Bias was called $Bias_{est}$. The corrected LAI (LAI_{cor}) was estimated according to **Equation 3.9**.

$$Bias = LAI_{ref} - LAI_{obs}$$

Equation 3.7

$$Bias_{est} = intercept + slopeB$$

Equation 3.8

$$LAI_{cor} = LAI_{LP-80\ ceptometer} + Bias_{est}$$

Equation 3.9

3.2.5.3. Moderate resolution Imaging Spectra- diameter leaf area index

LAI estimates from the remotely sensed level4 Moderate resolution Imaging Spectra- diameter (MODIS) global LAI and Fraction of photosynthetically Active Radiation (FPAR) product, also

referred to as the MCDISA3H product (see <https://modis.gsfc.nasa.gov/data/dataproduct/mod15.php>) were obtained for certain periods. The periods selected were the drought period event 2014- 2016 (Xulu, et al., 2018) and for 2018 January and June, corresponding to just prior to the “harvest date” used in CABALA. The images from the MCDISA3H product are compounded every 4 days at 500m pixel size (<https://lpdaac.usgs.gov/products/mcd15a3hv006/>). The data sets of this product include LAI, FPAR, a quality assurance rating, and standard deviation for each variable. The LAI data was selected by the tiled method and used GIS to extract the coordinates of the study.

3.3. Weather data

The CABALA model requires daily climate data. However, the software does allow mean monthly data to be input, which is then disaggregated to generate pseudo- daily data. Daily climate data includes daily maximum temperature, minimum temperature, radiation, and rainfall, whilst the monthly climate data requires monthly maximum temperature, minimum temperature, radiation, mean annual precipitation, total rain days, lowest temperature, and highest temperature.

As mentioned in **Chapter 0**, weather data for South Africa, particularly forestry regions, is a problem. Three approaches to sourcing estimates of weather at the locations of the study sites were used.

3.3.1. Monthly long-term weather data

The South African Atlas of Climatology and Agro- Hydrology, published in 2007 was described in literature review in *Section 2.4.2*. The 2007 long-term mean of fifty years (1959- 1999) was used as a first, “base” weather dataset. Importantly, this long-term dataset would represent a typical “non-droughted” climate. It did not include drought events such as were seen in the rotations of our study trees. The data were available as monthly mean average, minima, and maxima which CABALA disaggregated the data into pseudo- daily data. South African Atlas of Climatology and

Agro- Hydrology weather data is available as raster files and shapefiles and QGIS was used to extract weather data for the study site coordinates.

3.3.2. Daily weather data

3.3.2.1. *Meteoland daily weather data*

Initially, an interpolated surface of actual daily data was created using the package Meteoland in the R system for statistical computing (<https://cran.r-project.org/web/packages/meteoland.html>). The product was created to interpolate data from various stations to provide data for the areas that lack measurements. Data interpolation was done for the plots using their coordinates. This approach was abandoned, however, as it became evident that the variability in the region was not being properly captured by the interpolation method. The low rainfall at dry sites was not being adequately captured in comparison to wet sites, and the variation between them was therefore artificially small.

3.3.2.2. *Nearest South African Sugarcane Research Institute (SASRI) and South African weather stations (SAWS)*

The second approach, which was adopted for model runs, was to use the nearest stations to the study sites. Three main data sources were available: data from the South African Weather Services (SAWS) (<https://www.weathersa.co.za>), VitalWeather Systems (<https://vitalweather.co.za>) and data from the South African Sugarcane Research Institute (SASRI) (<https://sasri.org.za>).

The SAWS is based on the SAWS Act (Act No 8 of 2001) and provides services to the general public (free of charge) and commercial services (charged pre request) (<https://www.environment.gov.za/statutorybodies/saws>). SAWS has been recording rainfall daily since 1836, and temperature and solar radiation has been recorded hourly since 1950. SAWS rainfall, temperature and solar radiation daily weather data was available for the growing period (2008-2018) of the study sites.

VitalWeather Systems (<https://vitalweather.co.za>) provides daily weather data obtained from Davis Vantage Pro2 weather stations to several African industries, including the forestry industry, and others that necessitate real time weather data and historical weather data.

SASRI collaborated with Mondi Forests and individual sugarcane farmers to establish weather stations in forest plantations (<https://sasri.org.za>). SASRI has three types of weather stations, namely automatic weather station, manual weather station and rainfall weather station. The automatic weather station recorded rainfall, temperature, and solar radiation, whereas the manual weather station recorded rainfall and solar radiation. Automatic weather data are downloaded daily, and records updated on the WeatherWeb. Manual weather stations and rainfall stations are captured and recorded every month or two, depending on the extra time required to process sunshine cards.

Weather station locations were plotted using QGIS software (*Figure 3.6*). Stations with a complete dataset for the period of 2008- 2018 and closest to “Marie-Curie CFF” and Kwambonambi compartments were given first preference to extract weather data from (*Table 3.6*). The second and third closest SAWS, SASRI, and Vital weather stations with a complete data set was used to patch data sets of those stations with incomplete data sets. Given the lack of alternatives, closeness of the stations to the study sites was considered the most important indicator of how indicative each station would be to the data at the actual site.

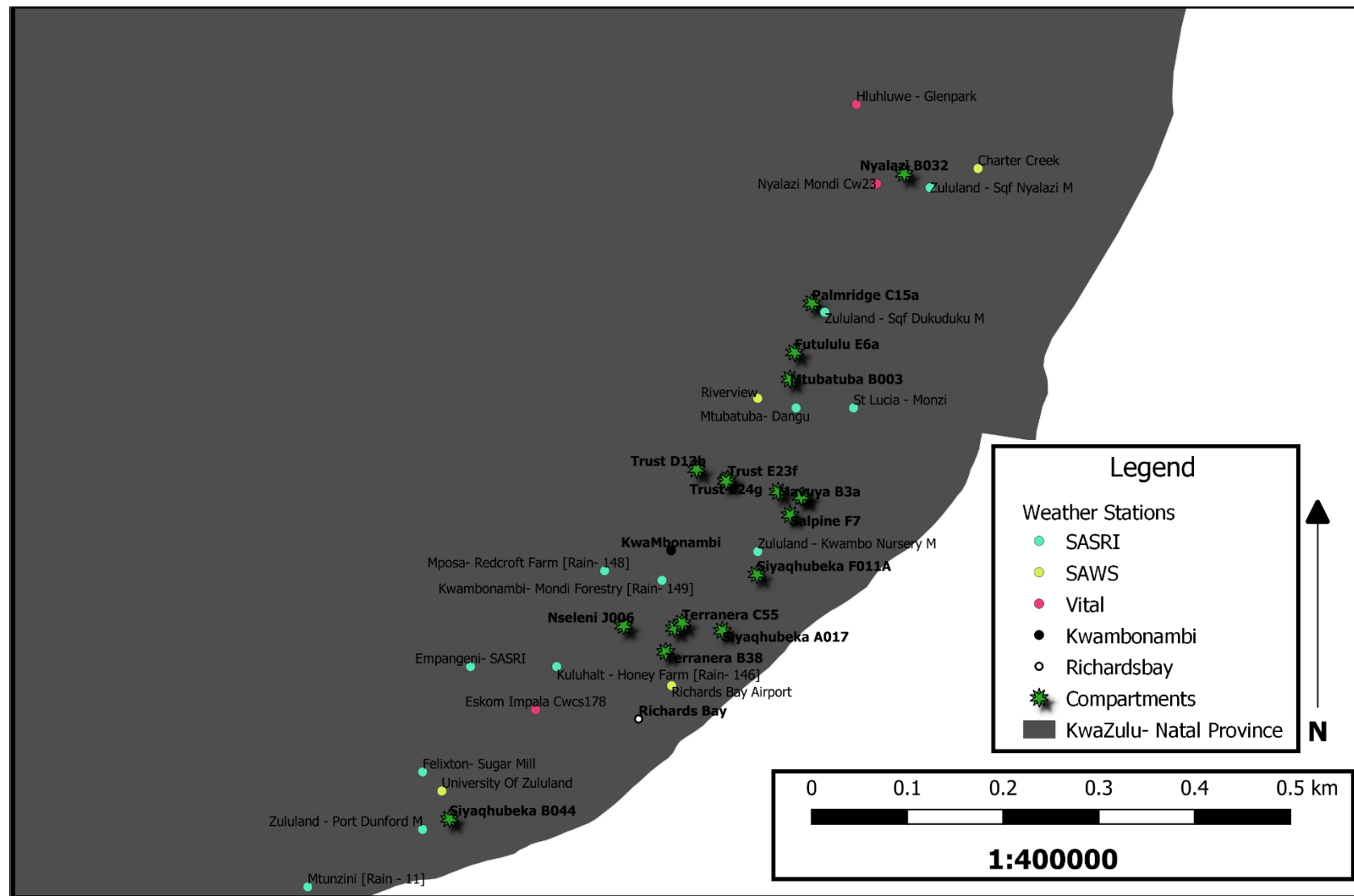


Figure 3.6: Map with all 18 compartments and surrounding SASRI, SAWS and Vital weather stations used to generate daily weather data.

Table 3.6: Compartments and their selected weather stations to compile weather data from 2008-2018. The first weather station is far right, the top line, followed by the next weather station after the slash ("/").

Compartment	Nearest station
Futululu E6a	Zululand - Sqf Dukuduku M / Mtubatuba-Riverview Sugarmill / Mtubatuba - Dangu / Riverview / St Lucia - Monzi
Mavuya B3a	Zululand - Kwambo Nursery M / Mtubatuba - Dangu / Riverview / Mtubatuba-Riverview Sugarmill / St Lucia - Monzi
Mtubatuba B003	Mtubatuba - Dangu / Mtubatuba-Riverview Sugarmill / Riverview / St Lucia - Monzi / Zululand - Sqf Dukuduku M
Nseleni J006	Kwambonambi-Mondi Forestry / Mposa-Redcroft Farm / Kuluhalt-Honeyfarm / Richards Bay Airport / Empangeni - Sasri
Nyalazi B032	Nyalazi Mondi Cw23 / Zululand - Sqf Nyalazi M / Charters Creek / Hluhluwe - Glenpark / Zululand - Sqf Dukuduku M
Palm_Ridge_C15a	Zululand - Sqf Dukuduku M / Mtubatuba-Riverview Sugarmill / Mtubatuba - Dangu / Riverview / St Lucia - Monzi
Salpine F7	Zululand - Kwambo Nursery M / Mtubatuba - Dangu / Mtubatuba-Riverview Sugarmill / Riverview / St Lucia - Monzi
Salpine G22b	Zululand - Kwambo Nursery M / Mtubatuba - Dangu / St Lucia - Monzi / Mtubatuba-Riverview Sugarmill / Riverview
Salpine G33b	Zululand - Kwambo Nursery M / Mtubatuba - Dangu / St Lucia - Monzi / Mtubatuba-Riverview Sugarmill / Riverview
Siyaqhubeka A017	Kwambonambi-Mondi Forestry / Richards Bay Airport / Zululand - Kwambo Nursery M / Mposa-Redcroft Farm / Eskom Impala Cwcs178
Siyaqhubeka B044	Zululand - Port Dunford M / University of Zululand / Felixton-Sugar Mill / Eskom Impala Cwcs178 / Mtunzini
Siyaqhubeka F011A	Zululand - Kwambo Nursery M / Kwambonambi-Mondi Forestry / Richards Bay Airport / Mposa-Redcroft Farm / Mtubatuba - Dangu
South Areas B35b	Kwambonambi-Mondi Forestry / Richards Bay Airport / Mposa-Redcroft Farm / Zululand - Kwambo Nursery M / Eskom Impala Cwcs178
Terranera C55	Richards Bay Airport / Kwambonambi-Mondi Forestry / Kuluhalt-Honeyfarm / Mposa-Redcroft Farm / Eskom Impala Cwcs178 / Zululand - Kwambo Nursery M
Terranera B38	Kwambonambi-Mondi Forestry / Richards Bay Airport / Mposa-Redcroft Farm / Zululand - Kwambo Nursery M / Eskom Impala Cwcs178
Trust D13	Riverview / Mtubatuba-Riverview Sugarmill / Zululand - Kwambo Nursery M / Mtubatuba - Dangu / Kwambonambi-Mondi Forestry
Trust E23	Zululand - Kwambo Nursery M / Riverview / Mtubatuba-Riverview Sugarmill / Mtubatuba - Dangu / Kwambonambi-Mondi Forestry
Trust E24	Zululand - Kwambo Nursery M / Riverview / Mtubatuba-Riverview Sugarmill / Mtubatuba - Dangu / Kwambonambi-Mondi Forestry

3.4. Physiological work

3.4.1. Greenhouse work: Specific leaf area versus leaf nitrogen content experiment

To estimate the SLA versus nitrogen content relationship in the *Eucalyptus grandis x urophylla* trees, an important CABALA parameter, a simple experiment was set up to determine the rate which SLA changes with nitrogen leaf content. This was determined by the ratio between dry mass of leaves (kg) and nitrogen content of leaves (kg).

To obtain this SLA: nitrogen ratio, twenty rooted cuttings of GU were transplanted at nine months old into 5 litre bags filled with 6 kg of sand. All growing medium adhering to the plants was washed off with tap water before transplanting. No fertilisers were added to the plant for eight weeks so that minimum nutrients, especially nitrogen, were present in biomass. The root cuttings received 200 ml of water through sprinklers in the morning at 09:00 am, 16:00 pm and 02:00 am.

A nitrogen treatment was initiated when the plants were 11 months old. The experiment was set up according to **Figure 3.7** with four nitrogen levels in the form of solids: N0, N1, N2, and N4 oriented east-west or north-south in the shade house. All pots received 1 gram of P and K. N0 received no nitrogen, N1 received 1 g of nitrogen, N2 received 2 g of nitrogen and N4 received 4 g of nitrogen (**Table 3.7** and **Table 3.8**). The schedule for this experiment which continued for two months and is illustrated in **Table 3.9**. Healthy, fully expanded leaves formed after the initiation of treatments were harvested for SLA determination and nitrogen content analysis. SLA was determined according to **Section 3.2.2**. SLA leaves were sent to a commercial laboratory bemlab (<http://www.bemlab.co.za>) for nitrogen analysis through total combustion.



Figure 3.7: The layout of the specific leaf area vs leaf nitrogen content experiment in the shade house.

Table 3.7: The nitrogen (N), phosphorous (P) and potassium (K) ratio for treatment N1, N2, N4, and N0.

Treatment	Nitrogen (g)	Phosphorous (g)	Potassium (g)
N1	1	1	1
N2	2	1	1
N4	4	1	1
N0	0	1	1

Table 3.8: The amount of fertilizer applied for each treatment. The Fertiliser is an NPK (28) with a ratio of 4:1:1; to ensure that those treatments ratios are met, according to Table 1, P and K will be added to ensure that there is 1 gram of N and P in each cocktail.

Treatment	4:1:1 (28) NPK fertiliser (g)	Additional Phosphorous (g)	Additional Potassium (g)
N1	5.36	0.75	0.75
N2	10.71	0.50	0.50
N4	21.43	0.00	0.00
N0	0	1	1

Table 3.9: Experiment schedule for the SLA vs leaf nitrogen content experiment.

Day	Treatment
11 December 2018	<i>Eucalyptus grandis</i> x <i>urophylla</i> root cuttings were transplanted into 5-liter pots filled with about 6 kg of soil.
28 January 2019	Rooted cuttings were moved outside the nursery and receive 200 ml of water per day through a dripper system.
28 February 2019	Plants received fertiliser according to Table 3.8 .
03 May 2019	Harvesting of leaves, SLA measurement, nitrogen analysis was done.

3.4.2. Glasshouse work: Hydrology experiment

A simple experiment was initiated to determine the lowest pre- dawn leaf water potential (LWP) of *Eucalyptus grandis x urophylla* hybrid seedlings by drying *Eucalyptus grandis x urophylla* cuttings seedlings gradually over a period of time (see method in **Section 3.4.2.1-3.4.2.2**). While the estimates from a glasshouse experiment in small plants will not fully represent the situation in larger field-grown trees, it was assumed that this approach would give a conservative estimate of the lowest pre-dawn water potential *Eucalyptus grandis x urophylla* can endure. That is, the levels found in this work would be those at which trees would at least be able to survive.

3.4.2.1. *Eucalyptus grandis x urophylla* rooted cuttings preparation

An experiment was conducted on 13-month-old, healthy *Eucalyptus grandis x urophylla* trees in 2.5 litre plastic pots. A transparent plastic film was used to cover the pot top surface and secured with tape to avoid direct evaporation from the medium. *Eucalyptus grandis x urophylla* root cuttings were moved into the glasshouse where the experiment was carried out. The glass house temperature was recorded every 10 minutes using temperature data loggers hanging on top of the root cuttings.

3.4.2.2. Irrigation regime

The experiment consisted of four blocks (block A, B, C, and D) and two treatments: the drought treatment and irrigation treatment (**Figure 3.8**). Each block consisted of 24 *Eucalyptus grandis x urophylla* root cuttings. Block A and B were placed on the east side of the glasshouse while block C and D were placed on the west side of the glass house. Block B and C received the irrigation treatment while block A and D received the drought treatment.

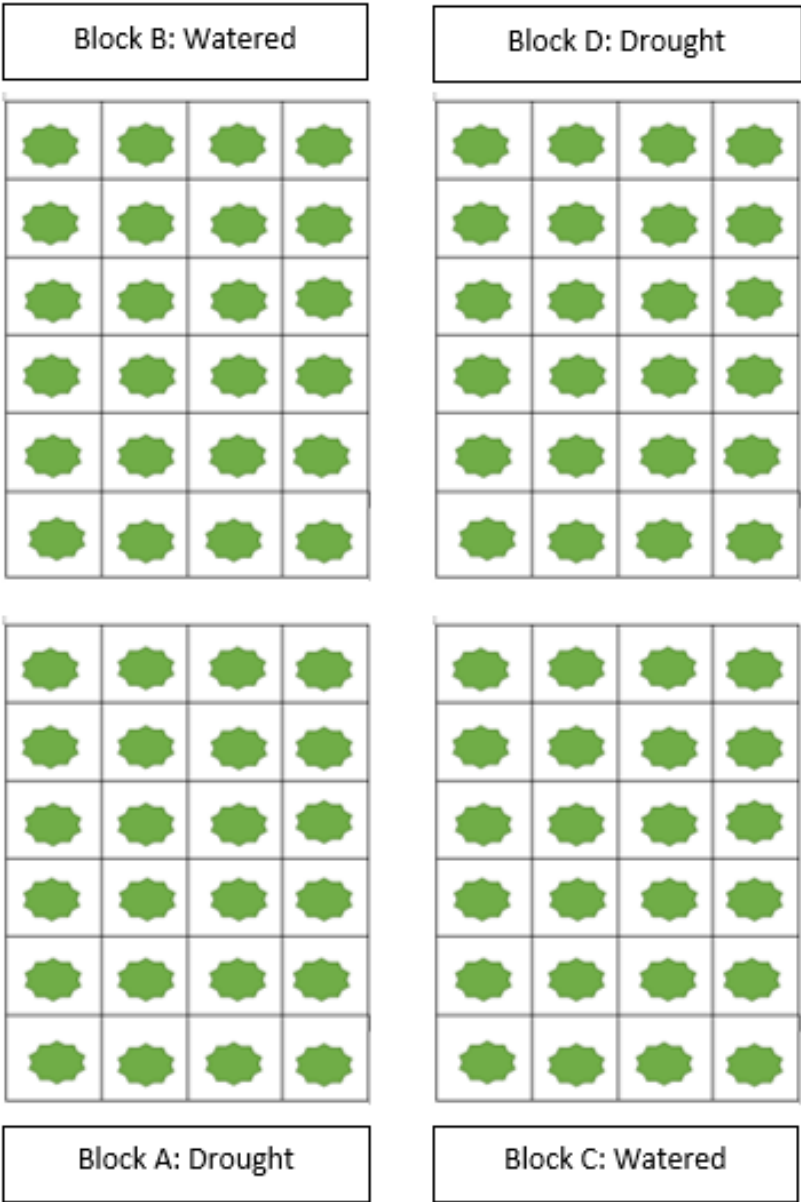


Figure 3.8: The layout of the leaf water potential experiment

Water (150ml) was supplied manually in the evening to *Eucalyptus grandis x urophylla* root cuttings in Block B and C for the whole duration of the experiment. The drought treatment, Block A and D, received water every 7th- 10th day following a previous watering (depending on the levels of incipient stress). This was done to gradually starve the plants for water without killing the plant. In the first watering of the drought treatment, pots were irrigated until field capacity was reached.

Table 3.10 was used as reference to know how much volumetric water the drought treatment plants were given.

Table 3.10: Volumetric water content and percentages for irrigation treatment.

Volumetric water content (ml)	% of volumetric water content
150	Field capacity (100%)
75	50
50	30
30	20
15	10

Plants were fertilised with a Wondersol all-purpose plant food organically based fertiliser. 20 ml of the product was added into a 1L water in a spraying bottle and sprayed over both irrigation and drought treatment root cuttings foliage on days which drought treatment was not receiving water. This treatment is labelled as “F” in **Figure 3.9**. On days when the drought treatment received water, irrigation water was mixed with 20ml water of the foliar product per 1L of water- this treatment is labelled as “T” in **Figure 3.9**. Leaves in the irrigation and drought treatment were green by the time the repeated fertilizer applications were finished and the fertiliser treatment was terminated.

Watered Treatment																															
Day of month		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Month	April																							150	150M24						
	May		150M22	150M20	F		F		F		150MT18	150M16	F		F		F		F	150MT14	150M12	F		F		F			150M10	150M8	
	June						150M6	150M4								M2															

Dry Treatment																															
Day of month		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Month	April																							150	M24						
	May		75M22	M20	F		F		F		75MT18	M16	F		F	75	F		F	75MT14	M12	F		F		F			30M10	150M8	
	June						15M6	M4								M2															

*Figure 3.9: Timeline of the hydrology experiment that was carried out in the glasshouse from the 23rd of April 2019 till the 15th of June 2019. The highlighted blocks indicate the days which each treatment was irrigated. The first number in the block refers to the amount of water (in ml) each *Eucalyptus grandis x urophylla* root cutting received per treatment. “M” stands for measurement cycle; it is the day LWP and *Eucalyptus grandis x urophylla* root cuttings pot weight was measured and recorded. “T” refers to the fertiliser treatments and “F” to foliage fertiliser treatment. The last number after “T” or “M” refers to the number of root cuttings present before harvesting.*

3.4.2.3. *Leaf water potential and pot weight measurements*

The stem diameter of the plants was measured 2 cm above the soil surface before the experiment was initiated. Two plants per block were randomly selected for LWP measurement for each cycle defined as the measurement day. A Scholander-type pressure chamber (model: SKPM 1405 50 bar analogue system) by Skye Instruments Ltd (<https://www.skyeinstruments.com/>) was used to measure leaf water potential (LWP). These measurements were made prior and post LWP measurements. LWP was measured at pre-dawn, early morning, midday, and late afternoon, on one leaflet with healthy fully expanded leaves.

3.5. Parameterisation of CABALA

A three-part approach was taken to estimating certain parameters for use with GU in South Africa. The three approaches were (1) to start with parameters published in the literature, followed by (2) estimates of selected parameters from lab-based and field experimental/sampling work and (3) to vary certain parameters within reasonable ranges to get the best fit against observed growth/stem volume data.

3.5.1. Published parameters

To start, the parameters already published and well-used for *E. globulus* were assumed. Wherever possible, these were then replaced using parameters developed for *Eucalyptus grandis x urophylla*. A table is given in *Section 2.4.3 (Table 2.4)* of parameters which could be sourced from published research.

3.5.2. Estimating allometric parameters from allometric relationships

3.5.2.1. Stand and tree structure parameters

Stand and tree structure parameters were estimated according to equations in *Table 3.11* which are also found in Appendix A-3. Battaglia, *et al.*, (2004). CABALA assumes bark biomass to be the function of stem biomass. Using the disc of wood sampled from “Marie-Curie CFF” sites, bark was fit into *Equation.10*. The maximum ratio between bark and bark + stem was estimated according to *Equation 11*.

The β_{V1} , β_{V2} , β_{V3} parameters involved in estimating stand total stem weight in CABALA were obtained by fitting stand total stem weight, calculated in *Table 3.5* using *Equation 9* in *Section*

3.2.4, to stand mean dominant height and stand basal area as indicated in *Equation 12*. In this study, the b and ε parameter was not included in *Equation 12* as the main interests were in the $\beta_{v1}, \beta_{v2}, \beta_{v3}$ parameters. $\beta_{v1}, \beta_{v2}, \beta_{v3}$ parameters were substituted in *Equation 14* so that $\beta_0 = \beta_{v1}, \beta_1 = \beta_{v2}$, and $\beta_2 = \beta_{v3}$.

Since there was no root sampling carried out in the study, the mean density of stem, branch and fine roots wood was assumed which was estimated from the branch and stem wood biomass, only, according to *Equation 13*. The biomass estimates were obtained from the field work described previously.

The model estimates the target mean ratio of tree height and mean tree diameter for stability as a function of ratio of crown weight to stem weight and total above- ground weight as shown in *Equation 18*. This target ratio is to maintain stability and force the model to adjust the height to diameter ratio to meet the target ratio upon growth increment, but without reducing height and diameter. Fresh crown weight was estimated as the sum of fresh leaves and branches of the whole tree in “Marie-Curie CFF” compartments, whilst stem weight was estimated as the sum of the fresh tree bole harvested in “Marie-Curie CFF” compartments. Fresh crown weight and stem weight water content was determine according to *Equation 3.2* in *Section 3.2.2*. The water content of the fresh crown weight and stem weight was subtracted to obtain the crown weight and stem weight. Sapwood cross sectional area is assumed to be a function of tree leaf area and stem height. The relationship between sapwood cross- sectional area and tree leaf area was estimated from Zhu, *et al.*, (2015) data set using *Equation 19*.

Specific leaf area is estimated by CABALA by *Equation 23*. The lower and upper specific leaf area was determined using the estimates made on samples as described in *Section 3.2.2* in *Equation 3.1*. The b_σ rate at which specific leaf area changes with leaf nitrogen concentrations, was obtained by applying *Equation 22* on leaf biomass from the nitrogen vs specific leaf area experiment. b_σ was assumed to be the average of b_σ for every seedling.

The lowest pre-dawn water potential to which trees will fall was assumed to be the lowest pre-dawn water potential observed in the drought series experiment in *Section 3.2.4*. Pre-dawn leaf water potential at field capacity was estimated from the drought series experiment using the data collected for the trees that received water daily.

Table 3.11: Equations used to determine stand and tree structure in CABALA according to Battaglia et al., (2004)

Equation No.	Estimate	Formula	Units	Abbreviation
10	W_b	$\beta_{Bk1} W_s^{\beta_{Bk2}}$	kg	<p>W_b = bark weight</p> <p>W_s = stem weight</p> <p>β_{Bk1}, β_{Bk2}, are parameters</p>
11	β_{Bk}^*	$\frac{W_b}{W_b + W_s}$	-	β_{Bk}^* = parameter for maximum bark to (bark and stem) ratio
12	V	$\exp\{\beta_0 + \beta_1 \ln(H) + \beta_2 \ln(B) + b\}$ $+ \varepsilon$	kg ha ⁻¹	<p>V = stand total volume according to equation 9.</p> <p>$\beta_0, \beta_1, \beta_2$ are parameters</p> <p>H = stand dominant height</p> <p>B = stand basal area</p> <p>b = the random plot effects with variance σ_b^2</p>

				ε = an independent within plot error with conditional variance $\text{Var} (V b) = \phi V_b^2$ where V_b is the conditional; expectation of V excluding the within plot error and ϕ is the dispersion parameter.
13	ρ_w	$\frac{d_m}{v}$	(kg DM m ⁻³)	ρ_w = density of wood d_m = mass of dry wood (kg) v = volume of wood (m ⁻³)
14	W_s	$\rho_w \beta_{v1} H_d^{\beta_{v2}} B^{\beta_{v3}}$	kg DM ha ⁻¹	W_s = stand total stem weight ρ_w = density of wood (kg DM m ⁻³) $\beta_{v1}, \beta_{v2}, \beta_{v3}$ are parameters H_d = stand mean dominant height (m) B = stand basal area (m ² ha ⁻¹)
15	W_{s-sw}	$\rho_w \beta_{v1} H_d^{\beta_{v2}} A_s^{\beta_{v3}}$	kg DM ha ⁻¹	W_{s-sw} = stem sapwood weight A_s = sapwood area (m ²)

16	R	$\frac{\text{crown weight}}{W_s}$	-	<p>R= ration of crown weight to stem weight</p> <p>$Crown\ weight$ = leaves + branches</p> <p>W_s = Stem weight + bark weight</p>
17	W_t	$W_s + W_b + W_f$	kg	<p>W_t = Total above ground biomass weight</p> <p>W_b = Branch weight</p> <p>W_f = Total foliage weight</p>
18	H/DBH	$\beta_{W1}R^{\beta_{W2}}W_t^{\beta_{W3}}$	-	β_{W1}, β_{W2} and β_{W3} are parameters
19	A_s	$\beta_{L1}H^{\beta_{L2}}A_F^{\beta_{L3}}$	-	<p>β_{L1}, β_{L2} and β_{L3} are parameters</p> <p>A_F = Tree leaf area</p> <p>H = Tree height (m)</p>
20	W_{i-sw}	$\rho_w \zeta L_i A_i$		<p>W_{i-sw} =weight of sapwood pool</p> <p>ζ =shape of i</p> <p>L_i = length of i</p>

				A_i =sapwood cross sectional area of i $i = \textit{Branches}$, Coarse roots
21	φ	$\frac{\sum_j^{largest\ tree} \varphi_j}{\sum_j N_j}$	°	N_j = number of branches j = branch number φ = branch to stem angle
22	b_σ	$\frac{W_f}{W_{Nf}}$	kg/kg	b_σ = rate of change of specific leaf area with leaf nitrogen concentration W_f = foliar weight (Kg) W_{Nf} = foliar nitrogen weight
23	σ	$\min \{ \max \{ \sigma_1, b_\sigma (\sigma_0 - \sigma_0) N_F \}, \sigma_0 \}$		σ =specific leaf area σ_0 = upper limit of specific leaf area σ_1 = lower limit of specific leaf area N_F = nitrogen concentration in the crown

3.5.3. Calibration and optimisation

CABALA has a large parameter set (150 parameters in total) and doing a full sensitivity analysis or optimization exercise (calibration /validation adjustments) for the full set was beyond the scope and most likely not necessary in this study. The approach taken was to start with the base parameter set published for *E. globulus* (Battaglia, et al., 2004), followed by changing those parameters considered most significant to get a revised set for *Eucalyptus grandis x urophylla* which could be confidently changed from literature, or adjusted from our experimental work and using data from the 18 plots.

3.5.3.1. Calibration

Parameters selected for calibration were those expected to have a major effect on CABALA estimates and performance, but difficult to measure or not readily available in literature are presented in **Error! Reference source not found..** The reason these parameters were selected was:

- i. *E. globulus* species are poorly temperature adapted to grow well in subtropical areas like Zululand because they exhibit lower optimum temperatures (T^*_{opt}) than eucalypts species or hybrids that grow in Zululand (Paton, 1980). In contrast, *Eucalyptus grandis x urophylla* grow well in subtropical and tropical conditions (Ferreira, et al., 2020), and should therefore exhibits higher optimal temperatures compared to *E. globulus*.
- ii. Trees regulate their stomatal conductance based on differences in supply and demand, which can be estimated to some extent from vapor pressure deficit and soil water potential as mentioned in **Section 2.1.1.3**. Thus, *Eucalyptus grandis x urophylla* hybrid parameters influencing stomatal conductance (f_{VI} and $pot1$) were targeted for adjustments.
- iii. As observed in field, *Eucalyptus grandis x urophylla* hybrids that was overthrown by wind had shallow roots that extended sideways and not downward to the soil. This indicated a

need to targeting the root extension rate parameter ∂z^*_R for adjustment for this *Eucalyptus grandis x urophylla* hybrid.

- iv. Ryan et.al. (2009) reported a lower construction respiration ratio (r_C) for *Eucalyptus grandis x urophylla* compared to the construction respiration ratio parameters used for *E. globulus* in Battaglia et al. (2004).
- v. An additional allometric parameter, the exponent stem height and diameter ratio equation, West₃ was included to the parameters selected for calibration as the *E. globulus* and *Eucalyptus grandis x urophylla* β_{w3} parameter resulted, based on observation, in errors in the estimated diameter to height ratio results in the CABALA model.

Table 3.12: Priority parameters to be adjusted to different levels for GU compared to the *E. globulus* parameters.

Parameter	<i>E. globulus</i>	Level 1	Level 2	Level 3	Level 4
T^*_{opt} - levels		30%	45%	60%	
T^*_{opt}	15	19.5	21.75	24	
f_{d1} - level		10%	20%	110%	%
f_{d1}	1	1.08	0.96	1.32	
f_{YI} - levels		10%	20%	110%	120%
f_{YI}	1.1	0.99	0.88	1.21	1.32
∂z^*_R - levels		30%	45%	60%	
∂z^*_R	250	175	137.5	100	
r_C - level		60%	40%	140%	160%
r_C	0.25	0.1	0.15	0.35	0.4
β_{w3} - level		5%	10%	15%	
β_{w3}	-0.136	-0.007	-0.0136	-0.0204	

3.5.3.2. Optimising parameter set by matrix table

CABALA was optimized by creating a matrix for respiration parameters k_{dav} and k_{d1} . k_{dav} and k_{d1} parameters were estimated from *E. globulus* by multiplying *E. globulus* parameters with 175%, 50% and 25% to create high, moderate, and low values, respectively, for the two parameters (**Table**

3.13). These percentages were selected to attempt to cover a reasonable range as there was no comprehensive sensitivity analysis done for the parameters in this study. The matrix design is illustrated in *Table 3.14*.

Table 3.13: k_{dav} and k_{d1} different levels for creating a matrix of the k_{dav} and k_{d1} respiratory parameters.

Parameter	<i>E. globulus</i>	High (H)	Moderate (M)	Low (L)
		175%	50%	25%
k_{dav}	0.03	0.0525	0.015	0.0075
k_{d1}	0.015	0.02625	0.0075	0.00375

Table 3.14: Matrix design of the k_{dav} and k_{d1} respiratory parameters.

k_{dav}	k_{d1}		
	0.02625	0.0075	0.00375
0.0525	HH	HM	HL
0.015	MH	MM	ML
0.0075	LH	LM	LL

**3.5.3.3. *Selecting the parameter that results to the best- fit
estimation of observed stand volume, mean diameter at breast
height and mean diameter***

Selected parameters for calibration and optimization in *Section 3.5.3.1* and *Section 3.5.3.2* were re-set at various levels according to *Table 3.12* and *Table 3.14*; one variable-at-a-time was changed from the *E. globulus* parameter set. The model was then run and estimates of stand mean DBH, height and volume obtained for daily and monthly weather data for all 18 sites. These were compared with actual data obtained in July 2018. The combination of parameters levels that resulted in the smallest RMSE and highest multiple R^2 and slope closest to were selected to construct a new, partially adjusted parameter set considered most suitable for *Eucalyptus grandis x urophylla*.

RESULTS AND DISCUSSION

4.1. Soils

Soils at all 18 study sites were predominantly sandy (**Table 4.1**), varying between sand, sandy loam and loamy sand. This is generally the case in Kwambonambi and surrounding areas in coastal Zululand (Smith, et al., 2001). These sandy soils experience free drainage due to their relatively low water holding capacity. There are sites which may experience waterlogging, but this is rare. Some of the soils in this region are known to be quite deep (in excess of 30 m) (Dovey, et al., 2011). While soil depth may be an important determinant of growth rate in *Eucalyptus grand x urophylla* (Haifei, et al., 2020), rooting characteristics are an important factor influencing the effect.

Smith et.al (2001) found that soil bulk density range between 1.382 and 1.789 g cm⁻³, which is similar to what was observed in this study. The observed bulk density ranges in these sites were between 1.17- 1.45 g cm⁻³, 1.28- 1.58 g cm⁻³, and 1.33- 1.57 g cm⁻³ at 0-10 cm, 10-20 cm and 20-50 cm soil depth respectively (**Table 4.1**). Such high bulk density is common in sandy soil (Smith & du Toit, 2005). Soil bulk density increased with soil depth in most compartments. An exception was at site Trust E24g where the bulk density decreased with soil depth. This could be due to topsoil compaction caused by heavy harvesting machines during harvesting operations (Smith & du Toit, 2005). Compaction decreases with soil depth, thus a higher bulk density in the topsoil, as seen in TrustE24g, and lower bulk density in the 10-20 cm layer and an even lower bulk density at 20-50 cm soil depth. This compaction, however, is unlikely to have a major impact on tree growth on these sites because of low clay (<10%) content within the 50 cm soil depth present in Zululand sandy soils (Smith & du Toit, 2005).

Table 4.1: Summary of soil physical properties (soil texture and bulk density) of soil samples obtained from the 18 study sites used for model verification.

Compartment	Soil depth and texture				Bulk density (t/m ³)		
	Soil depth (cm)	Texture	Soil depth (cm)	Texture	Soil depth (0-10 cm)	Soil depth (10-20 cm)	Soil depth (20-50 cm)
Trust D13b	0-120	Sand			1.418	1.419	1.441
Nyalazi B032	0-20	Sandy Loam	20-120	Loamy Sand	1.171	1.428	1.479
Mtubatuba B003	0-50	Loamy Sand	20-120	Sandy Loam	1.173	1.434	1.440
Futululu E6a	0-120	Sand			1.388	1.467	1.466
Palmridge C15a	0-120	Sand			1.333	1.378	1.402
Salpine F7	0-10	Loamy Sand	10-120	Sand	1.382	1.542	1.501
Mavuya B3a	0-30	Loamy Sand	30-120	Sand	1.266	1.410	1.400
Trust E23f	0-120	Sand			1.236	1.278	1.440
Terranera B38	0-60	Sand	60-120	Loamy Sand	1.301	1.430	1.412
Trust E24g	0-20	Loamy Sand	20-120	Sandy Loam	1.448	1.400	1.331
Salpine G22b	0-120	Sand			1.286	1.526	1.478
Salpine G33b	0-60	Loamy Sand	60-120	Sand	1.349	1.567	1.455
South Areas B35b	0-120	Sand			1.395	1.419	1.441
Terranera C55	0-120	Loamy Sand			1.376	1.436	1.471
Siyaqhubeka B044	0-120	Loamy Sand			1.395	1.563	1.567
Nseleni J006	0-120	Loam Sand			1.352	1.581	1.516
Siyaqhubeka F011A	0-120	Sand			1.265	1.442	1.446
Siyaqhubeka A017	0-120	Loam Sand			1.374	1.493	1.469

Typical of sandy sites in a sub-tropical region like coastal Zululand (Dovey, et al., 2014), all of the sites had relatively low soil organic carbon and nitrogen content across all soil depths, with an overall average of 0.41% (± 0.012) and 0.024% (± 0.0019), respectively (**Figure 4.1- A & Figure 4.1- B**). Soil organic carbon content was highest in the 0-10 cm soil depth in all sites. A decrease of soil carbon content with soil depth was observed at most sites. However, at some sites the lowest soil carbon content was, unexpectedly, found at a soil depth of 10-20 cm. Despite different soil sampling depths for soil organic carbon analysis, the same trends were observed in subtropical climates sites Jaguariaiva and Ventania in Brazil, where the top layer had the highest soil contents; with Jaguariaiva soil organic carbon decreases with soil depth and Ventania having the lowest soil organic carbon content on the middle soil depth (Ferreira, et al., 2020).

The mean soil organic carbon in these two Brazilian subtropical sites is 1.61%, which is about four times more than the soil organic carbon observed in Kwambonambi sites. The highest soil organic carbon (1.5%) and nitrogen (0.06%) content was observed in the 0-10 cm soil depth of Mavuya B3a. In comparison with soil organic content in subtropical climates sites Jaguariaiva (1.6 – 2.36%) and Ventania (0.73 – 2.10%) in Brazil, and the soil nitrogen content in subtropical climate sites Lancang River (0.05- 0.095%) basin in China, Kwambonambi soil organic carbon and nitrogen was undoubtedly very low. Low organic carbon and nitrogen content observed in Kwambonambi soils can be explained by the quick drainage of sandy soils and low clay content in the study site (Dovey, et al., 2011), where relatively heavy summer rainfall results in leaching of nutrients (Vadigi & Ward, 2013).

What is very interesting is that planted forests on the Zululand coastal plain have high productivity potential despite low apparent fertility (Dovey, et al., 2011). An interesting and likely reason for this is the high levels of atmospheric deposition of nitrogen in a form of NH_4^+ , NO_3^- and NO_2^- added into the ecosystem.

Activities such as regular sugarcane burning in the north of Zululand, Richards Bay industrial area biomass burning, vehicle emissions, rural fires, organic matter rich sea spray from the marine and pollution transported from inland are possible sources of nitrogen deposition into the study sites. This is an important point of consideration, and must be borne in mind, when assessing CABALA performance at some sites with (apparently) very low N.

The C:N ratio, required for CABALA runs, decreased with soil depth at most sites (**Figure 4.1-C**). The lowest and highest average C:N ratio throughout the 0-50 cm soil depth is observed in Siyaqhubeka B044 (11.22 ± 1.19) and Mavuya B3a (23.75 ± 0.69) respectively. Overall, the average C:N ratio at the 18 sites over the 0- 50 cm soil depth was 16.68 ± 0.74 . In general, the decomposition rate increases with an increase of the C:N ratio (Hu, et al., 2019). The CERES-type sub-model in CABALA uses the C:N ratio to determine the index for the decomposition rate (CNRf) (Godwin & Jones, 1991). A value of one is assumed for C:N ratios below the presumed critical C:N ratio of 25. The CNRF value starts to decrease exponentially as the C:N ratio becomes larger than the critical C:N ratio 25. In the Zululand sites, a CNRF will be one because of C:N ratios below 25, however CABALA reduce decomposition rates to a limit for soils with high C:N ratio and low nitrogen concentrations (Godwin & Jones, 1991).

Kwambonambi compartments had, overall, slightly acidic soil pH (H₂O) (5.5 ± 0.15) over all three soil depths, ranging from 4.67 to 6.69 (**Figure 4.1-D**). Like many eucalypt species, *Eucalyptus grandis x urophylla* grows more successfully on acidic soils compared to alkaline soils (Aggangan, et al., 1996). Haifei et al. (2020) and Aggangan et al. (1996) reported an increase of stem diameter and height with a decrease of pH for *Eucalyptus grandis x urophylla* (1-15 years old) and *Eucalyptus urophylla* seedlings respectively. This can be explained by the reduced effectiveness of growth promoting ectomycorrhizal fungi at increased pH levels (Aggangan, et al., 1996). Due to the small pH variation in the 18 sites, there was not a strong correlation between stem diameter or height vs soil pH observed in this study. However, it is important to be aware that slightly acidic pH is an important factor in generally facilitating the high productivities seen at these sites.

Haifei et al. (2020) and Aggangan et al. (1996) reported an increase of stem diameter and height with a decrease of pH for *Eucalyptus grandis x urophylla* (1-15 years old) and *Eucalyptus urophylla* seedlings respectively. This can be explained by the reduced effectiveness of growth promoting ectomycorrhizal fungi at increased pH levels (Aggangan, et al., 1996). Due to the small pH variation in the 18 sites, there was not a strong correlation between stem growth and soil pH observed in this study. However, it is important to be

aware that the lower pH is an important factor in generally facilitating the high productivities seen at these sites.

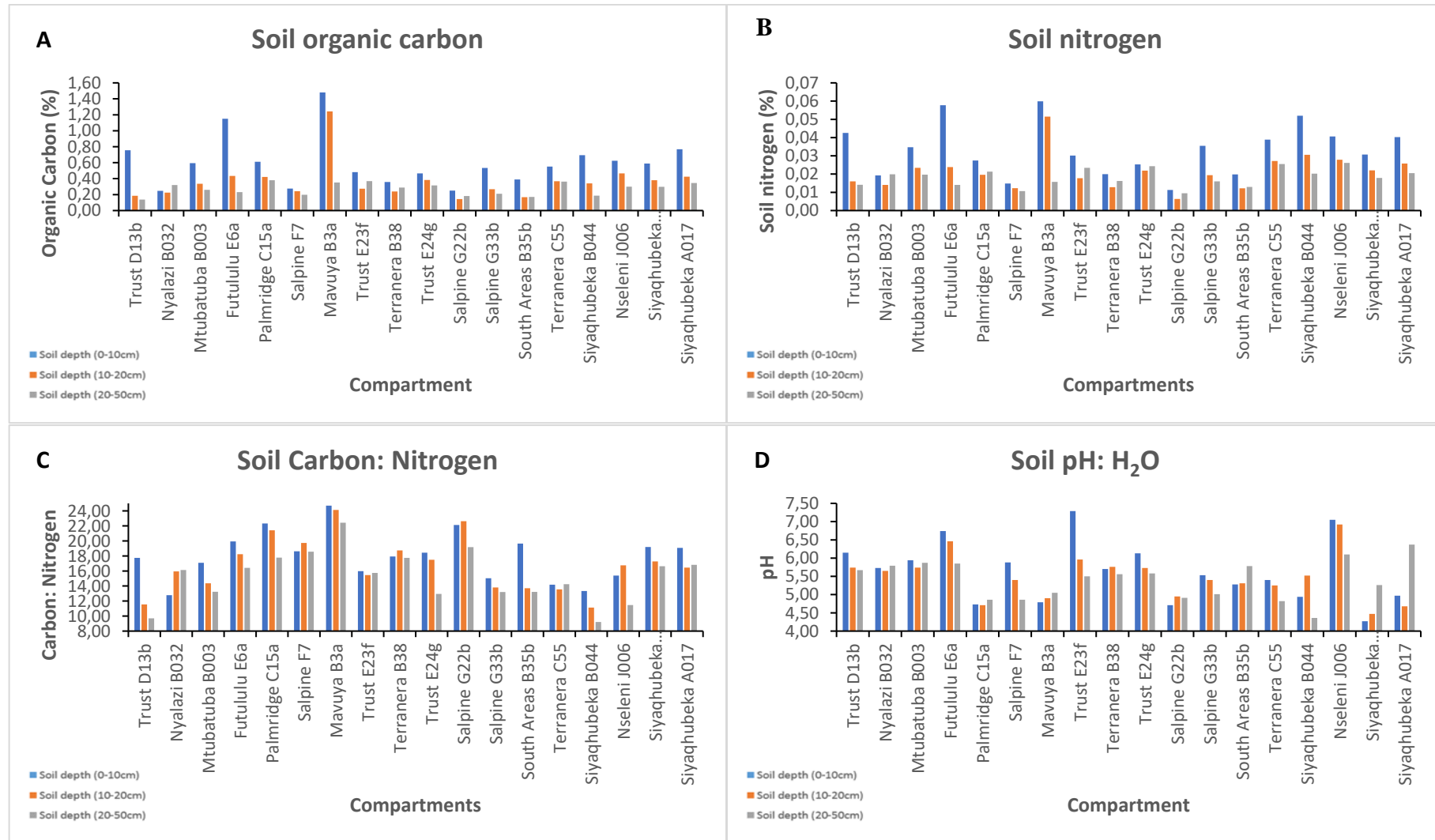


Figure 4.1: Soil chemical properties description from the study site soil samples over three soil depths 10-20, 20-30 and 30-50cm

4.2. Weather

Sites in the northern Zululand coast, over the long term, received less mean annual precipitation (836-974 mm) compared to sites located in the southern coast of Zululand (1247-1281 mm) (**Figure 4.2**). Sites located between the two “extremes” received mean annual precipitation ranging between 1118-1139 mm. This pattern of mean annual distribution along the Zululand coastline is well established (du Plessis & Zwolinski, 2012). In addition, the mean annual precipitation increases as you move closer to the coastline (du Plessis & Zwolinski, 2012).

It is also clear from **Figure 4.2** that sites planted in 2008 experienced conditions markedly drier than average at the time of planting. This difference decreased in 2011 and 2012, when rainfall was closer to the long-term mean. The region experienced a record-breaking drought (Xulu, et al., 2018) in 2014 and 2015 when rainfall was, in some years, less than half the long-term mean. Xulu et al. (2018) reported this drought as being 2014 – 2016, but it is notable that by 2016 (**Figure 4.2**) there was evidence of a turn in the trend and rainfall was increasing again. This is of particular importance in understanding the growth of these stands in terms of actual conditions experienced and this is a good example of when models like CABALA can be so useful in integrating periods of drought into overall growth projections. *Eucalyptus grandis x urophylla* is not considered a sustainable choice on sites with rainfall of less than 988 mm (Herbert, 2012). However, sites in the north coast received much less rainfall (**Figure 4.2**) than 988 mm which suggests that this is not so clear-cut. However, it cannot be denied that extended periods of such drought will lead to critical reductions in productivity and likely mortality (Crous, et al., 2017).



Figure 4.2 Mean annual precipitation (MAP) of long-term conditions (MAP_monthly) and actually experienced conditions (MAP_actual) in Kwambonambi compartments from 2008- 2018

The maximum mean annual temperature (26.33 °C - 27.58 °C) in the long-term data was lower in most years compared to the data from 2008 - 2018. Between 2008 - 2018, sites on the north coast experience higher maximum mean annual temperature ranging between 27.11 and 27.85 °C while sites in the mid and south coast of the Kwambonambi area experienced slightly lower maximum mean annual temperatures ranging between 26.33 and 26.98 °C. Also note that these regions experienced not only very dry conditions but also extreme temperatures in 2015, especially in the north coast of Kwambonambi.

The long-term minimum mean annual temperature ranged between 16.46 °C and 17.49 °C. Actual minimum mean annual temperatures from 2008 were cooler than this at most sites (**Figure 4.3**).

The opposite was observed in many sites in the south coast, (Terranera B38, South Areas B35b, Terranera C55, Siyaqhubeka F011 and Siyaqhubeka A017). Mean minimum annual temperatures fluctuated upwards in most sites in the north (from Trust D13b upwards) in the 10-year dataset from 2008 onwards. Sites in the mid-coast and south coast experienced a downward fluctuation of the actual experienced mean minimum annual temperatures which made these sites cooler with years. Siyaqhubeka B044 was an exception.

The long term mean radiation was higher than what was recorded between 2008 – 2018. But two factors must be noted; first, 2008 – 2018 data were only from two stations, second, it is not clear what effect interpolation had on the results in the long-term mean data.

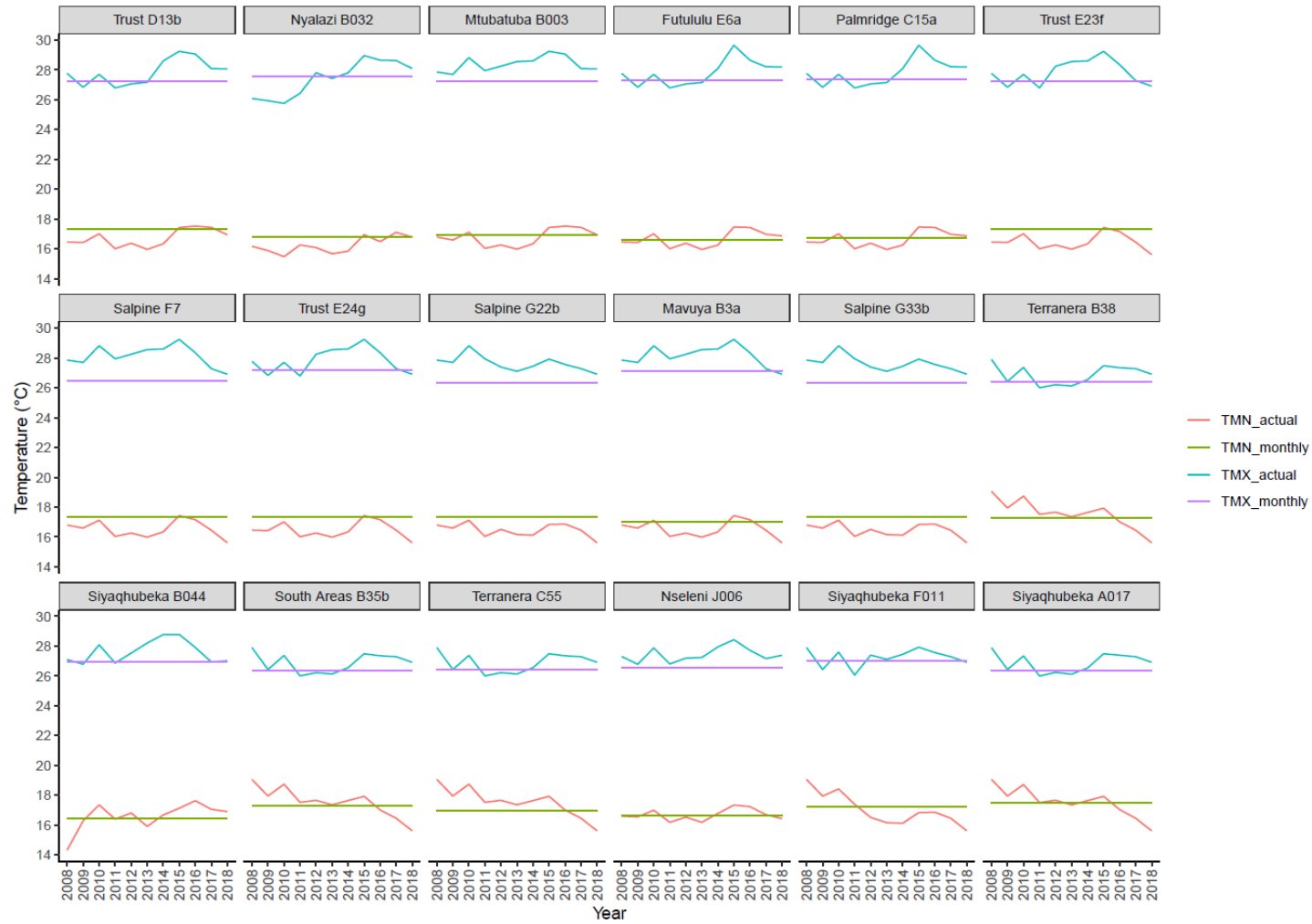


Figure 4.3 Long-term mean maximum (TMX_monthly) and minimum (TMN_monthly) annual temperatures, and actual annual mean maximum (TMX_actual) and minimum (TMN_actual) annual temperatures at the study sites near Kwambonambi.

4.3. Biomass in the “Marie-Curie CFF” compartments

4.3.1. Leaf area index from “Marie-Curie CFF” sites

The leaf area index (LAI) as estimated from destructive sampling at the five “Marie-Curie CFF” sites ranged between about 3 and 7 (**Figure 4.4**). Destructive LAI generally decreased (Salpine G22b > Trust E23f > Trust E24g > Trust D13b) with rainfall. An age effect was also observed in the destructive LAI between Trust E23f, Salpine G33b and Trust E24g which is a decrease of LAI with age. While LAI values of greater than 4 or 5 are possible for eucalypts (e.g. Battaglia et al 1998), it was surprising to get such high values in this study. Eucalypt plantations in South Africa would typically not have LAI values of much above a value of about 6 (see, for example, Dovey and Du Toit 2006). A factor could be the presence of large numbers of epicormic shoots at some sites which increased total leaf mass (although not strictly in the canopy). It is otherwise not clear why some sites were showing such high values.

There was a correlation of 69.1% with a standard error of 1.5 between the Bias (difference between the reference destructive LAI and observed ceptometer LAI) and stand basal area. The corrected ceptometer LAI overestimated LAI in three sites (Trust D13b, Salpine G33b, Trust E24g) and underestimated LAI in the other two sites (Trust E23f and Salpine G22b). Interestingly, the corrected ceptometer LAI in the elder stands was close to the reference destructive LAI Salpine G22b (10.0 years old) and Trust E24g (10.1 years old). Corrected ceptometer LAI increased with age, this can be explained by the increase of branch biomass with age observed in **Figure 4.6** that are included when ceptometers reading are taken below the canopy. The LAI difference between MODIS and the reference destructive sampling method was small at three of the sites but marked at the slower growing sites.

The LAI difference between MODIS and the reference destructive sampling method was small at three of the sites but marked at the slower growing sites.

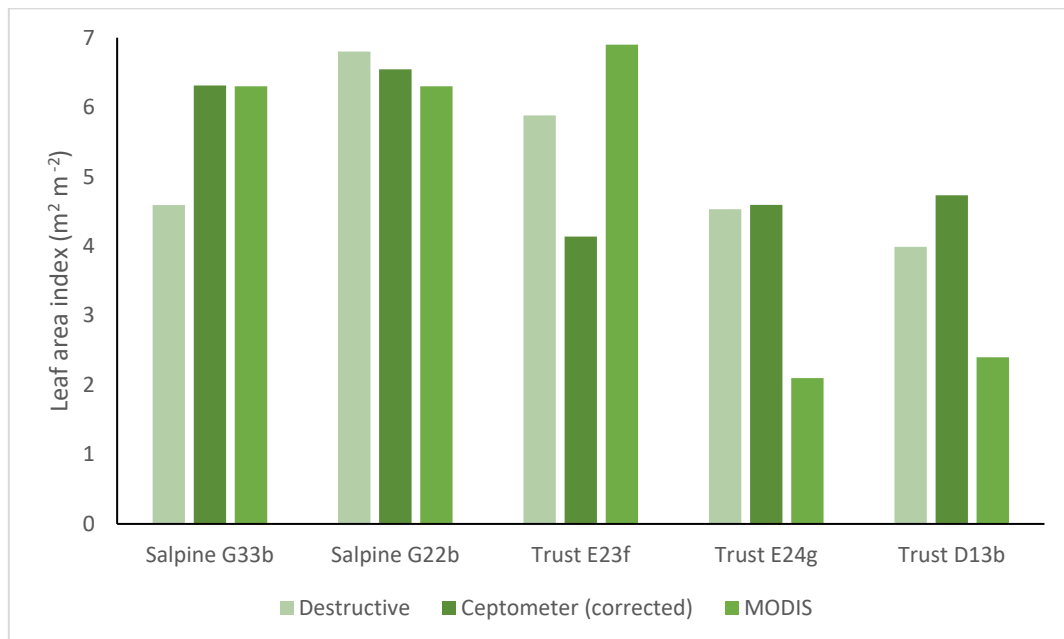


Figure 4.4: Leaf area index (LAI) estimated from three methods (destructive sampling, LP-80 ceptometer and MODIS products) at the five “Marie-Curie CFF” sites in June 2018.

4.3.2. Biomass allocation

Total above-ground biomass increment for 2018 (**Figure 4.5**) and biomass compartment proportions (**Figure 4.6**) varied markedly among compartments. In all five “Marie-Curie CFF” compartments, stem mass was the largest proportion of total above-ground biomass (72.54%) followed by bark (17.28%), branches (8.83%) and finally foliage (3.51%).

However, at site Trust D13, a very low productivity site, the proportion of stem was lowest, and bark highest. At the two higher productivity sites (Salpine G22b and Salpine G33b) there was a relatively high proportion of branch biomass. Extensive epicormic shoots were observed at Trust D13b (low productive site) and Trust E24g (moderate productive site). This suggested that the trees had responded to drought stress. It may have contributed to a lower allocation to stem mass.

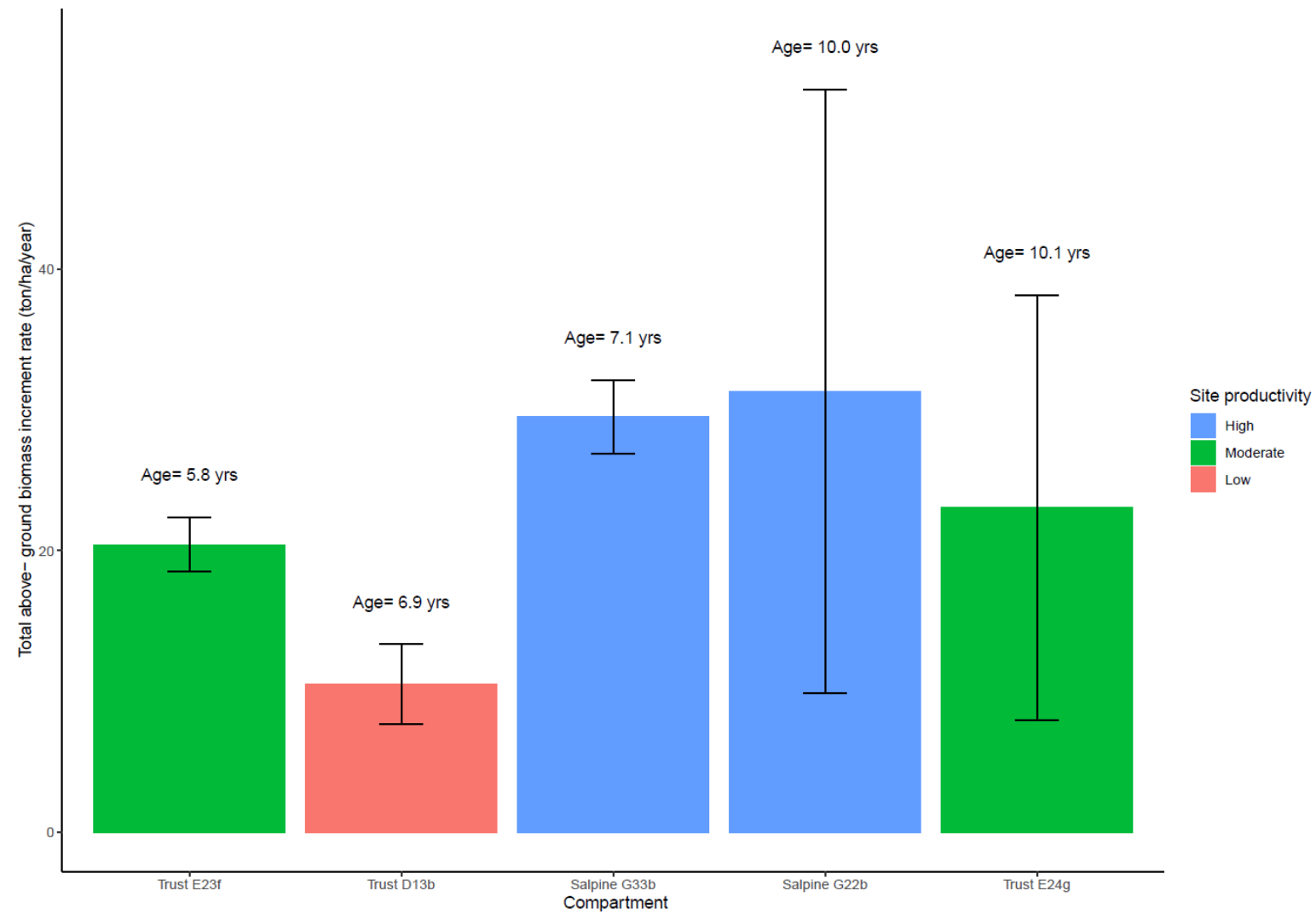


Figure 4.5: Above-ground biomass increment in “Marie-Curie CFF” compartments (where yrs= years).

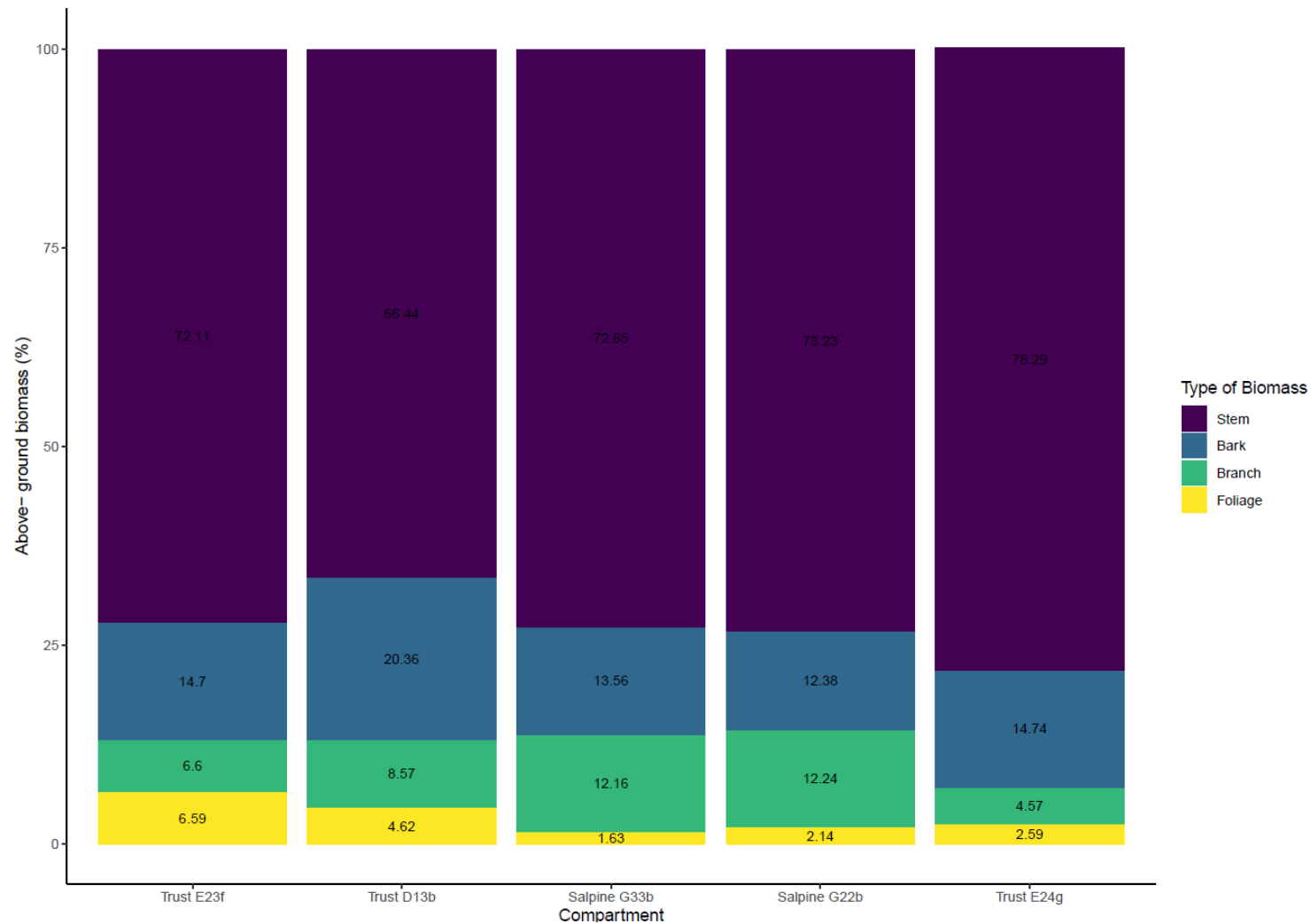


Figure 4.6: Biomass proportions in “Marie-Curie CFF” compartments based on samples taken in June 2018. Sites Trust E23 and Trust were under 7 years old. Salpine G33b was above 7 years old and the other sites were 10 years old.

4.3.3. Biomass Allometry

The biomass relationships using material selected for this study is highly consistent with broader models of above-ground biomass (AGB) for *E. grandis* in the region (**Figure 4.7**) and also for *E. nitens* (a cold-tolerant eucalypt not found in Zululand). Based on an analysis by Dr S. Dovey using classified SAPPI data (Dovey pers. Comm 2019), it was clear that the model of AGB for the *Eucalyptus grandis* x *urophylla* clone planted in the 18 sites fell clearly within the same range of data for other eucalypt species (*E. grandis* and *E. nitens*). Based on an exponential model, tree-level DBH explained 94% of the variation in AGB for the *Eucalyptus grandis* x *urophylla* varieties in the present study (**Figure 4.7**).

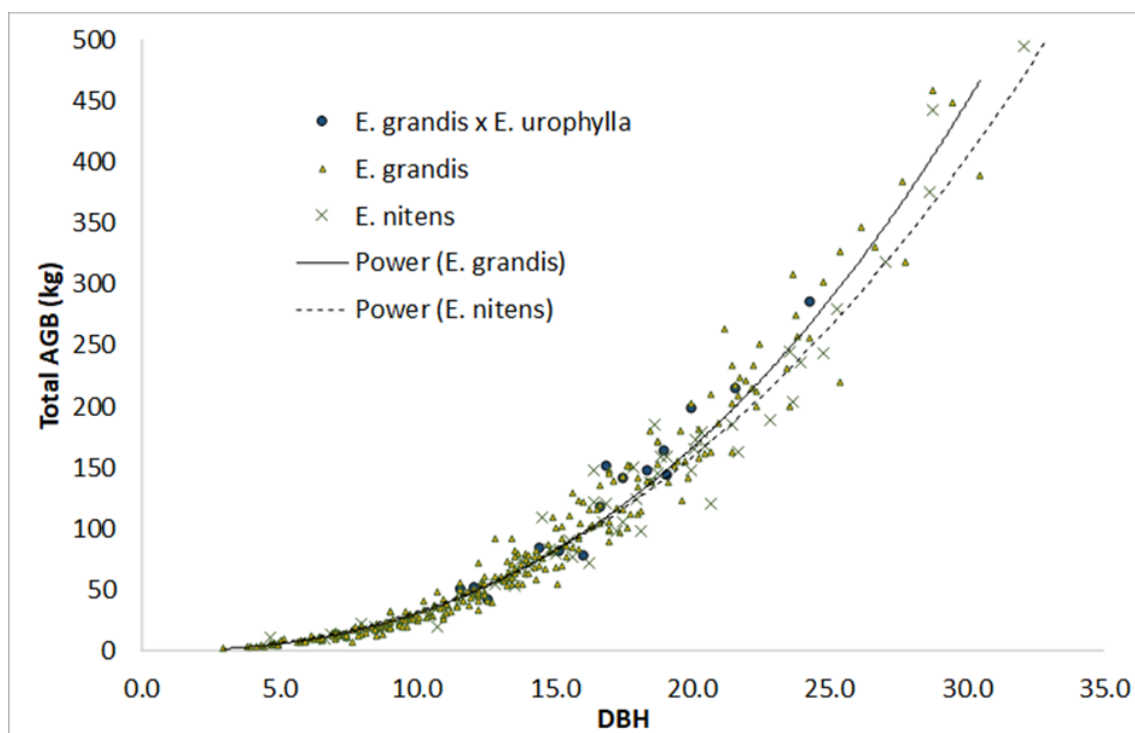


Figure 4.7: Allometric models of total above-ground biomass (AGB) of three commercial eucalypt varieties. Analysis courtesy of Dr S. Dovey (SAPPI).

The log transformed bark and stem mass was also highly correlated, with a multiple R^2 of 0.93 (**Figure 4.8**). The maximum ratio bark/ (bark + stem) was 0.16 which is very close to the *E. grandis* value of 0.15 assumed by Battaglia et. al (2004). This suggest that there is a small difference between the two species in terms of maximum ratio bark:/ (bark + stem).

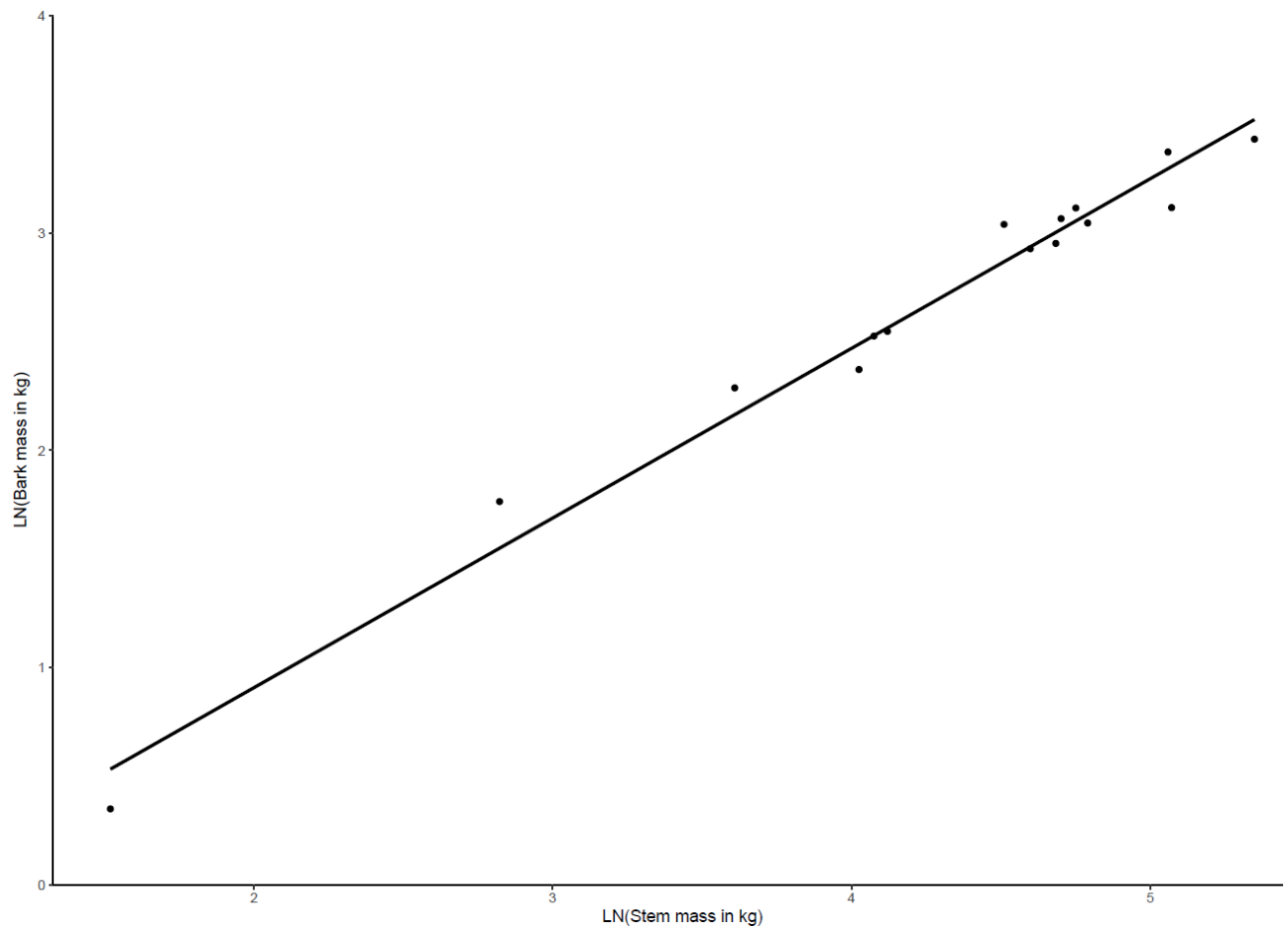


Figure 4.8: A linear regression graph for transformed stem and bark mass data obtained from trees sampled from the five “Marie-Curie CFF” sites.

4.4. Stand structure description

Compartments were divided into three mean annual increment (MAI_{2018}) categories estimated from the 2018 DBH and height inventory data (obtained for all sites). The MAI_{2018} categories are the lowest ($9\text{--}17.99 \text{ m}^3/\text{ha}/\text{years}$), medium ($18\text{--}26.99 \text{ m}^3/\text{ha}/\text{years}$), and higher ($27\text{+} \text{ m}^3/\text{ha}/\text{years}$) MAI_{2018} categories. On average, MAI was $27.65 \text{ m}^3/\text{ha}/\text{year}$ ($\text{se}=3.0$, $\text{sd}=12.93$) across all compartments. It is worth noting that the trees were different ages when this MAI was estimated in 2018.

Overall, mortality was low. The average mortality at all 18 sites combined was 5.66% ($\text{se}=1.25$, $\text{sd}=5.29$), ranging from 0% to 9.24% . The three mortality outliers (Siyahubeka B044, Terranera C55, and Siyahubeka A017) (**Figure 4.9**) are in the highest MAI_{2018} category. Siyahubeka F011A experienced the highest tree mortality while Nyalazi B032 did not experience any mortality (**Figure 4.9**).

Average mean DBH and the DBH distribution skewness of all 18 sites combined is 15.06 cm ($\text{se}=0.59$, $\text{sd}=2.51$) and 0.06 respectively. DBH distribution at the 18 sites was fairly symmetrical with a slight tendency towards a negative skewness at some sites. It is likely that the most recent innovation of CABALA (Battaglia & Bruce, 2017) would be able to capture these distribution changes in the simple stand structure and would be an interesting further study.

The widest average diameter distribution was observed in the highest MAI_{2018} category with Siyahubeka F011A followed by Siyahubeka B044. Siyahubeka A017 on the other hand has the narrowest diameter distribution in this category.

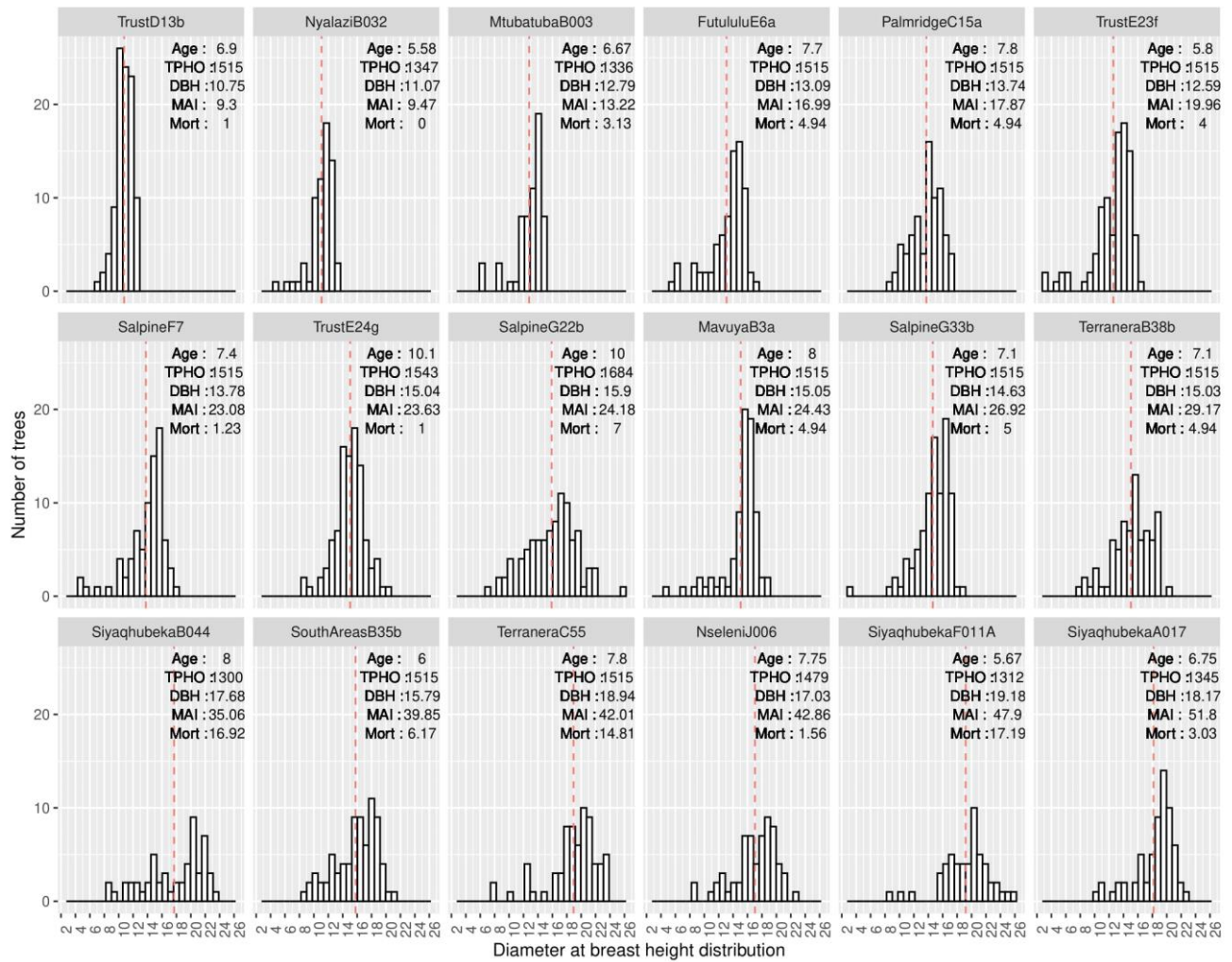


Figure 4.9: Diameter distribution of the 18 compartments, observed in year 2018, in Kwambonambi, where age is in years, TPHO is trees per hectares at establishment age, DBH is the stand mean diameter at breast height in cm and represented by the dotted line, MAI is mean annual increment in m³/ha/year and Mort is tree mortality in percentages.

4.5. Specific leaf area and nitrogen concentration relationship

There was a clear linear relationship between specific leaf area and leaf nitrogen concentration in the nursery experiment (**Figure 4.10**) with a multiple R^2 of 0.62, which is useful for estimating a key parameter, $b\sigma$ (the rate of change of specific leaf area with leaf nitrogen concentration) in CABALA. Battaglia et al (2004) published $b\sigma$ (the Rate of change of specific leaf area with increasing leaf nitrogen concentration) as 70 kg (dry mass) kg^{-1} (Nitrogen) for *E. globulus*. Here, for *Eucalyptus grandis x urophylla*, it was estimated to be 90 kg (dry mass) kg^{-1} (Nitrogen) which is higher than the value used for *E. globulus*.

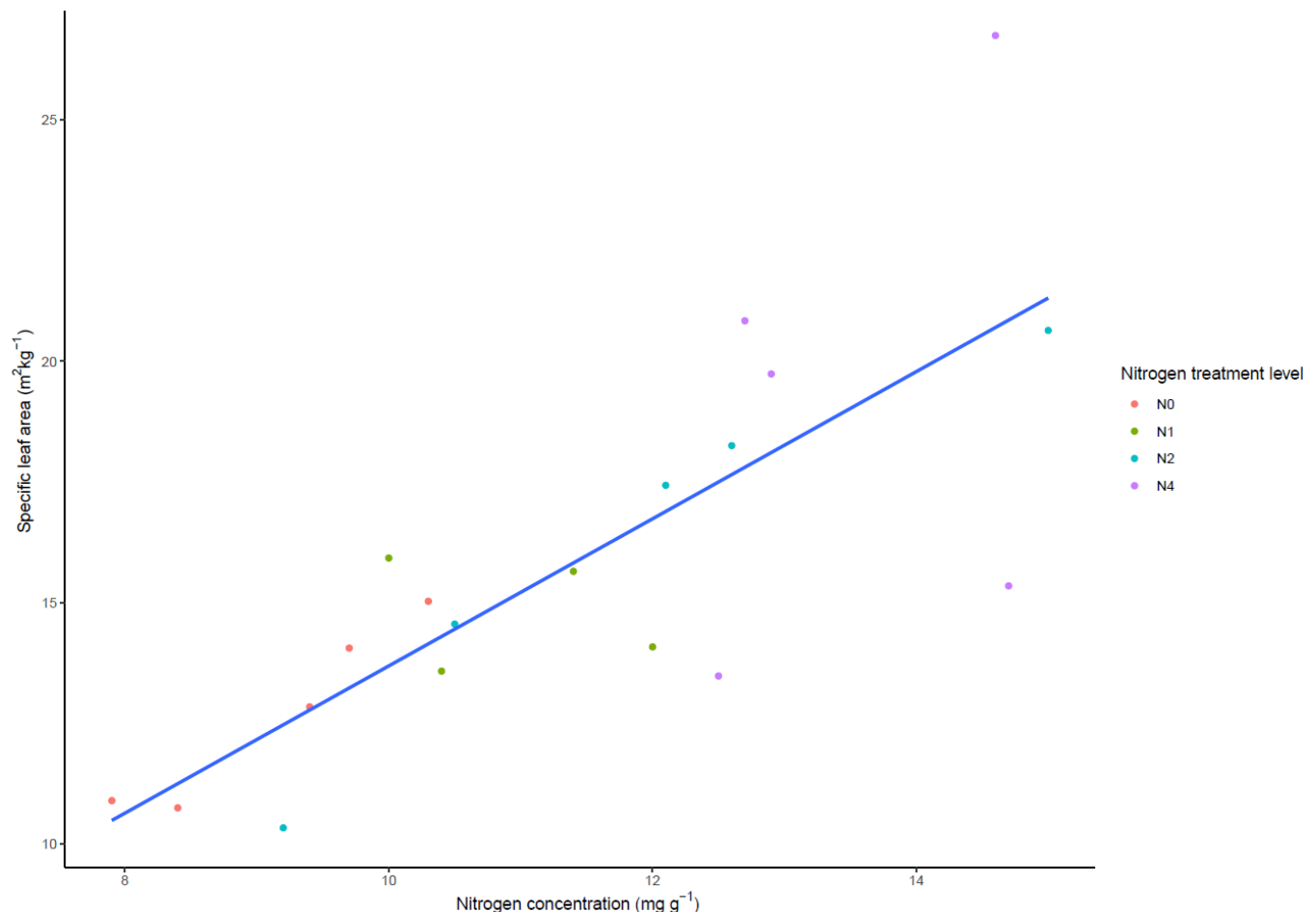


Figure 4.10: A linear regression graph for specific leaf area (SLA) and leaf nitrogen concentration.

4.6. Pre-dawn leaf water potential in *Eucalyptus grandis* x *urophylla* seedlings

Based on a monitoring experiment using small trees (1-year old cuttings), pre-dawn leaf water potential (PDLWP) dropped to a minimum of -4.2 MPa in the drought treatment during the experiment period (**Figure 4.11**). Trees wilted markedly but were able to subsequently recover from this low value following re-watering. Given that this value is very low, but not lethal, it was assumed a reasonable level for the minimum value parameter required by CABALA.

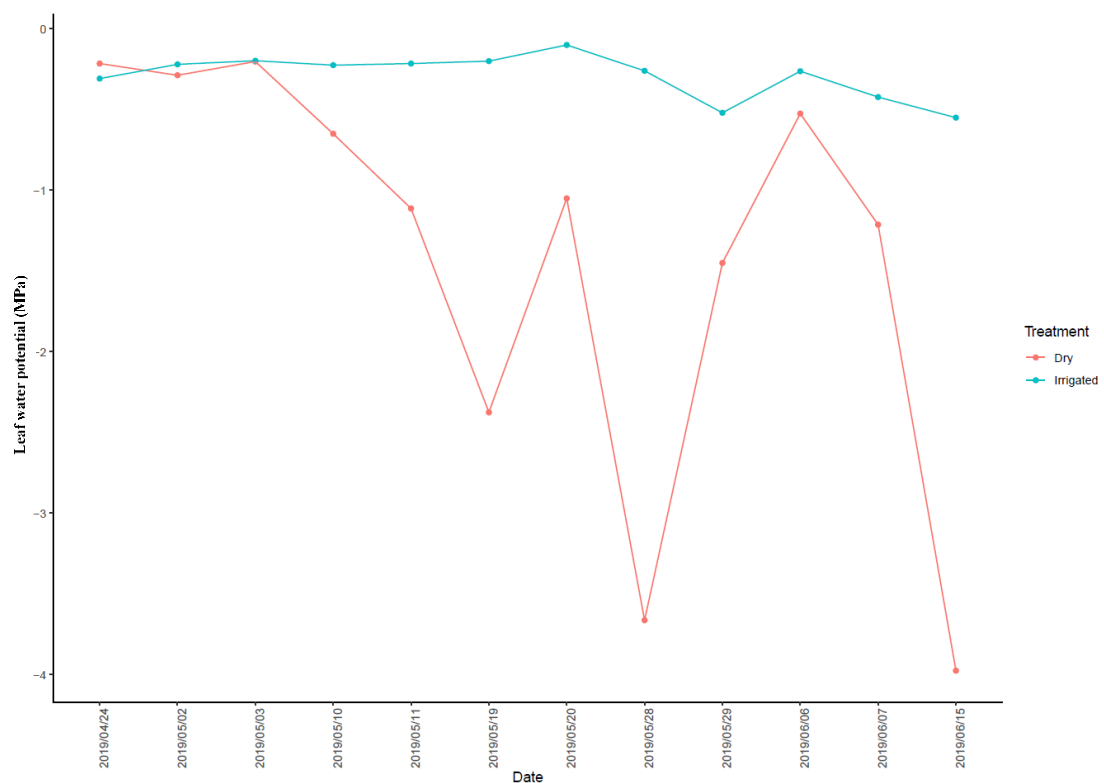


Figure 4.11: Pre-dawn leaf water potential over a series of drought treatments.

4.7. The CABALA model output

4.7.1. CABALA output when simulated using the *Eucalyptus globulus* parameter

When the model was run using the *Eucalyptus globulus* (2004) parameter set, already 65% of the variance in stand volume was explained using the long-term interpolated weather dataset and 67% when using data from stations between 2008 – 2018 (*Table 4.2*, *Figure 4.12*, and *Figure 4.13* and). Overall, however, the slope of the fitted line was substantially less than 1 in both cases, indicating that the model was under-predicting volumes in the stands. Stand volume at some sites were particularly badly predicted. These were Siyaqhubeka F011a, South Areas B035b and Siyaqhubeka A017.

Table 4.2: Statistical summary of the relationship between observed volume and simulated volume for the long term mean conditions and actual experienced daily conditions.

Stand descriptive variable	Statistical summary	Long-term mean data	2008 – 2018 data
Stand volume (m ³ / ha)	RMSE	62.11	136.34
	Multiple R ²	0.65	0.67
	slope	0.56	0.20
Diameter at breast height (cm)	RMSE	2.09	3.16
	Multiple R ²	0.58	0.72
	slope	0.82	0.48
Mean height (m)	RMSE	5.35	8.29
	Multiple R ²	0.64	0.49
	slope	0.36	0.19

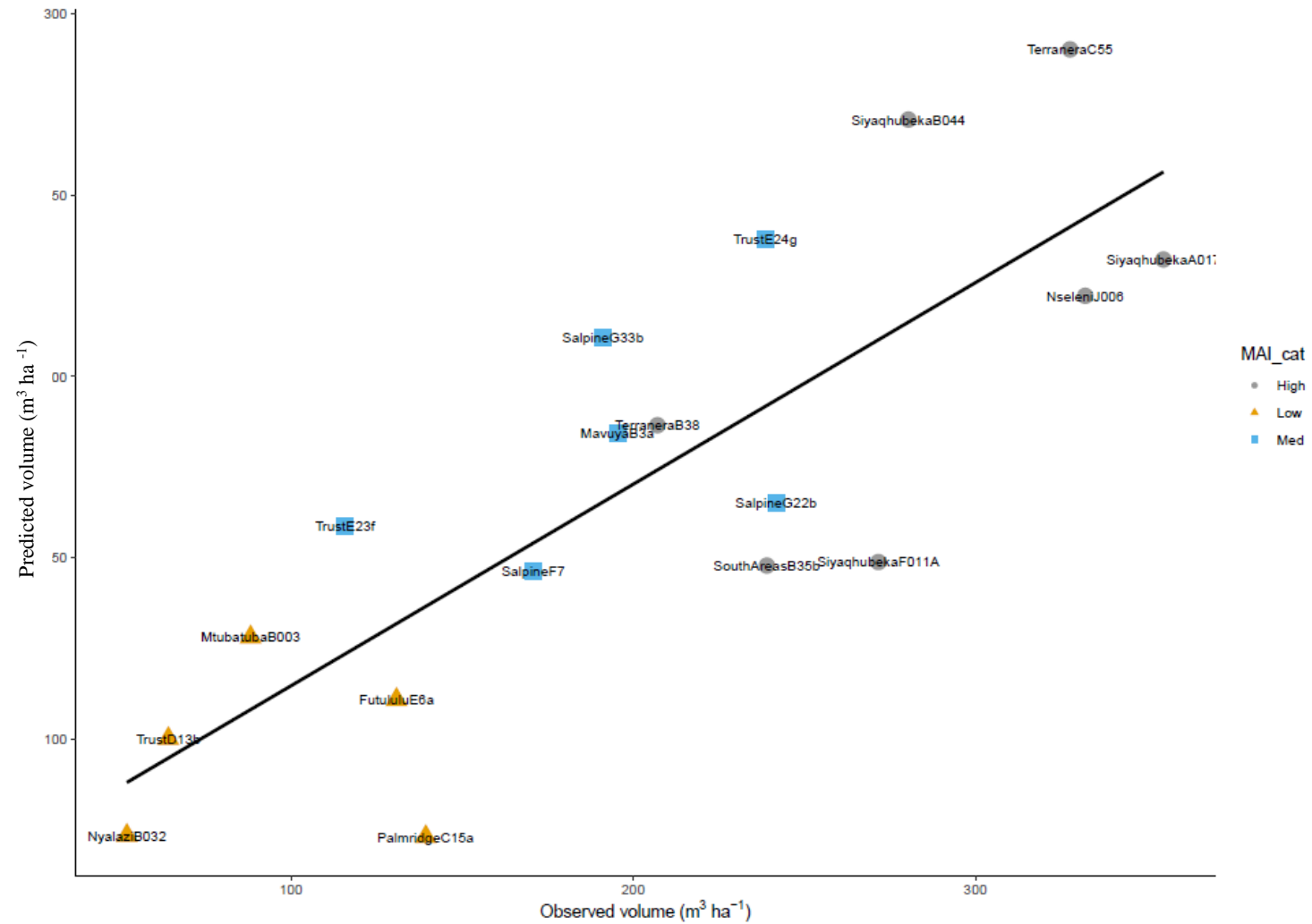


Figure 4.12: Observed and predicted stand volume of E. globulus using the long-term monthly weather data source. MAI_cat is the mean annual increment category defined in Section 4.4 (based on prior records for the stands).

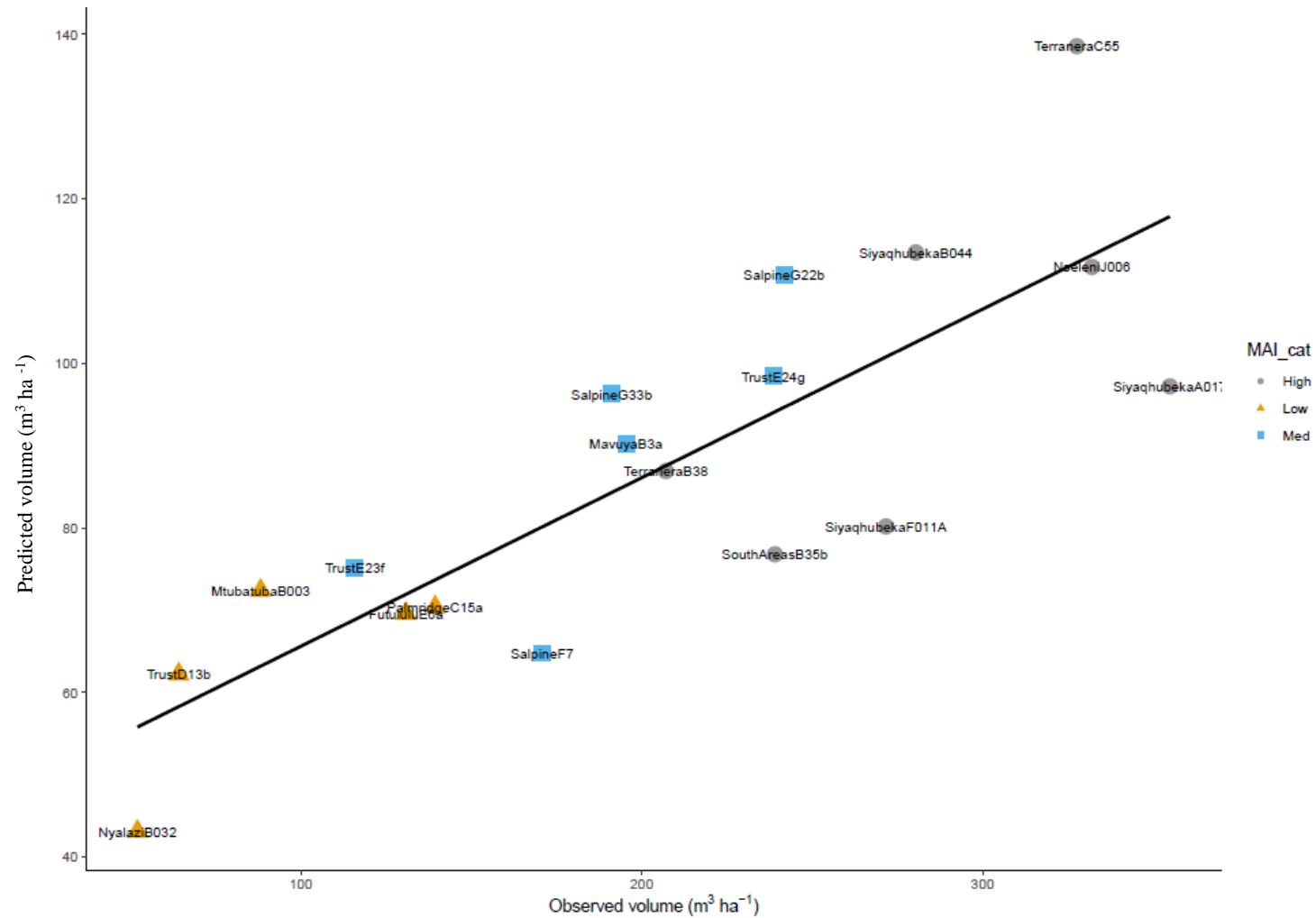


Figure 4.13: Observed and predicted stand volume of E. globulus using the actual experienced weather data. MAI_cat is the mean annual increment category defined in Section 4.4 (based on prior records for the stands).

4.7.2. CABALA output when simulated using the *Eucalyptus grandis x urophylla* new parameter set

4.7.2.1. Diameter at breast height trajectory

Following the development of a parameter set more suitable for the *Eucalyptus grandis x urophylla* hybrid, the correlation between the observed and estimated diameter at breast height (DBH) was 54.61% and 67.84% when using the long term conditions and 2008 – 2018 weather data as input, respectively. That is, the prediction was better when the actual weather data (for the period 2008 – 2018) was used as compared to the long-term mean.

The estimated DBH trajectory has a fast initial growth either way (**Figure 4.14** and **Figure 4.15**), which is expected in *Eucalyptus grandis x urophylla* grown in South African climates. When using long-term mean data, DBH was generally over-estimated (**Figure 4.14**). This would be expected, as the trees, in reality, experienced much drier conditions than the long-term mean. As soon as the 2014-2016 drought period was introduced (using the actually experienced conditions for the modelling) (**Figure 4.15**), the model better estimated DBH. Interestingly, in reality the trees at the higher MAP sites continued to grow during the 2014-2016 drought period as if the trees were not affected by the drought (e.g. Siyaqhubeka A017, Siyaqhubeka B044 and F011A). The model did not capture this effect and overly “penalised” growth for these sites. In general the DBH estimated with actually experienced trajectory followed the observed growth trajectory closely in all low MAP sites and five of the moderate MAI₂₀₁₈ sites.

It may be that the capacity to explore the soil was not correctly estimated here. Possibly at these wetter sites the trees had already tapped into a deeper portion of the profile in which stored water remained readily available.

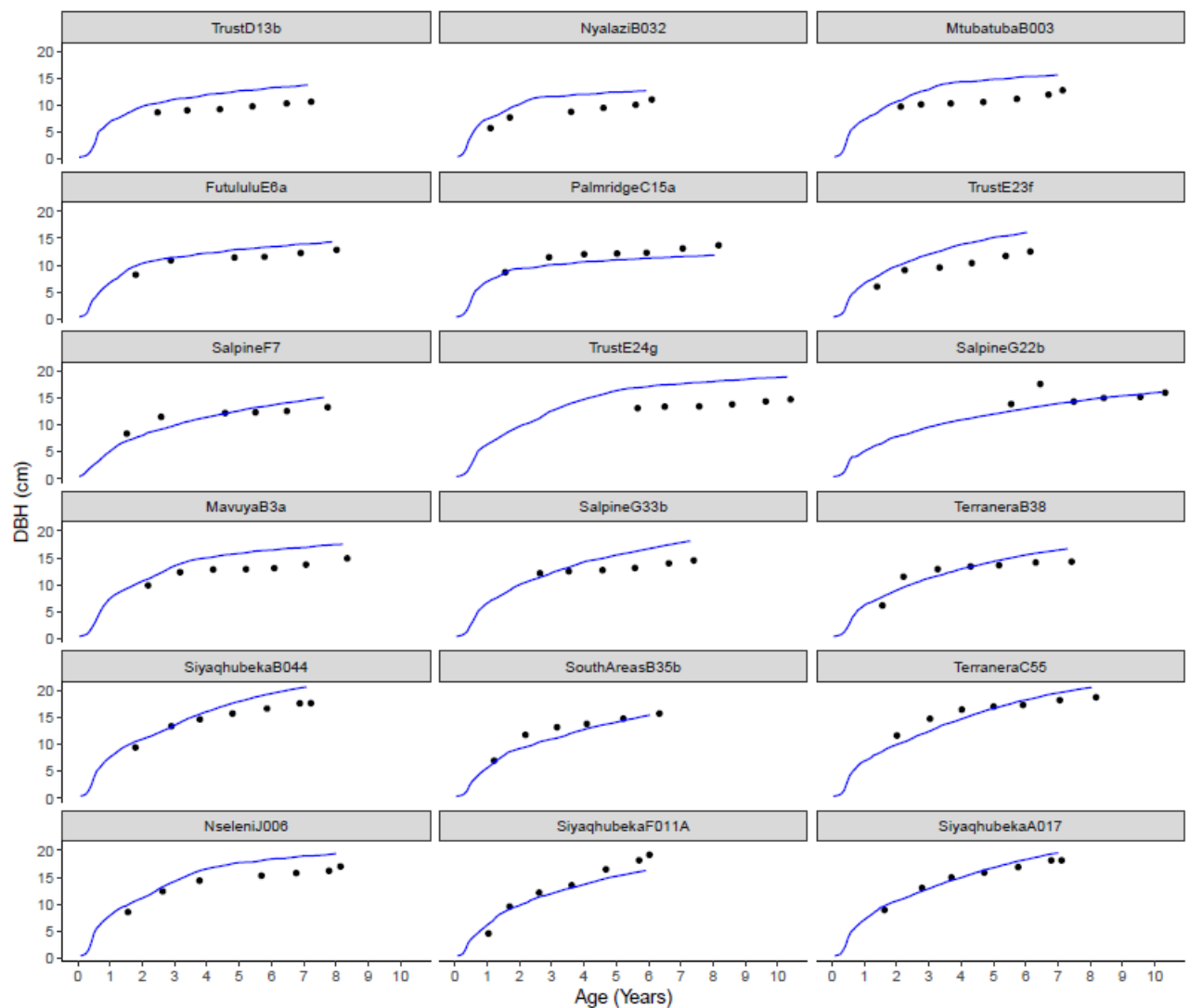


Figure 4.14: Observed (dots) and predicted (lines) DBH trajectories using long-term mean monthly weather data 1.

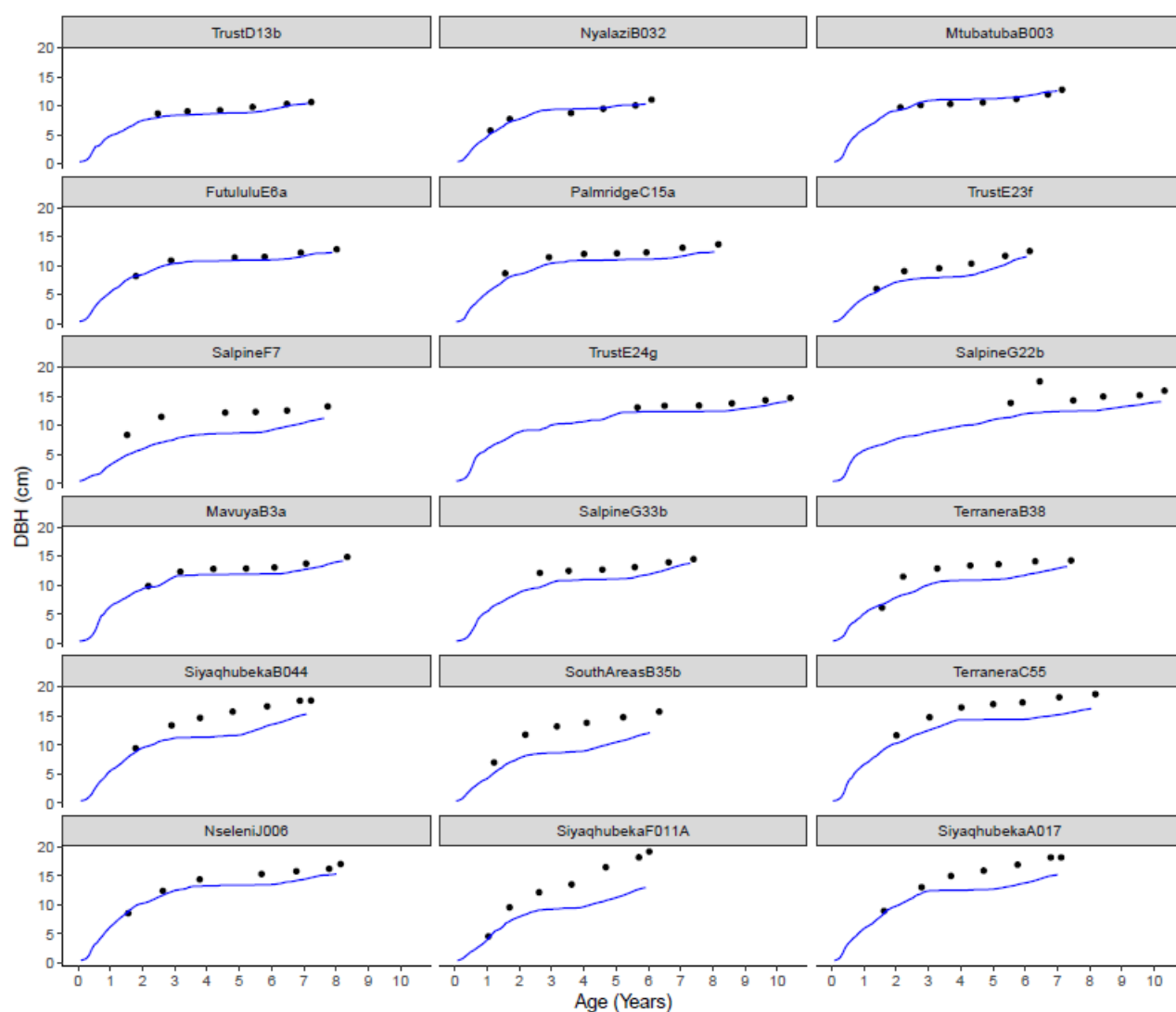


Figure 4.15: Observed (dots) and predicted (lines) DBH trajectories using weather data from actual stations between 2008 and 2018.

4.7.2.2. Stand height trajectory

Like DBH, the estimates of stand height trajectories were also generally overestimated when long term mean data were used (**Figure 4.16**). The most serious height overprediction was in dry sites with low MAI. When weather data from the period 2008 – 2018 were used, height trajectories tended to under-predict against actual measurements at about 83% of the sites with most severe underpredicitions in the high MAP sites (Siyaqhubeka A017, Siyaqhubeka B044, Siyaqhubeka F011A and South Areas B35b) (**Figure 4.17**). Only at Trust D13b did the model perfectly capture estimated stand height development over time.

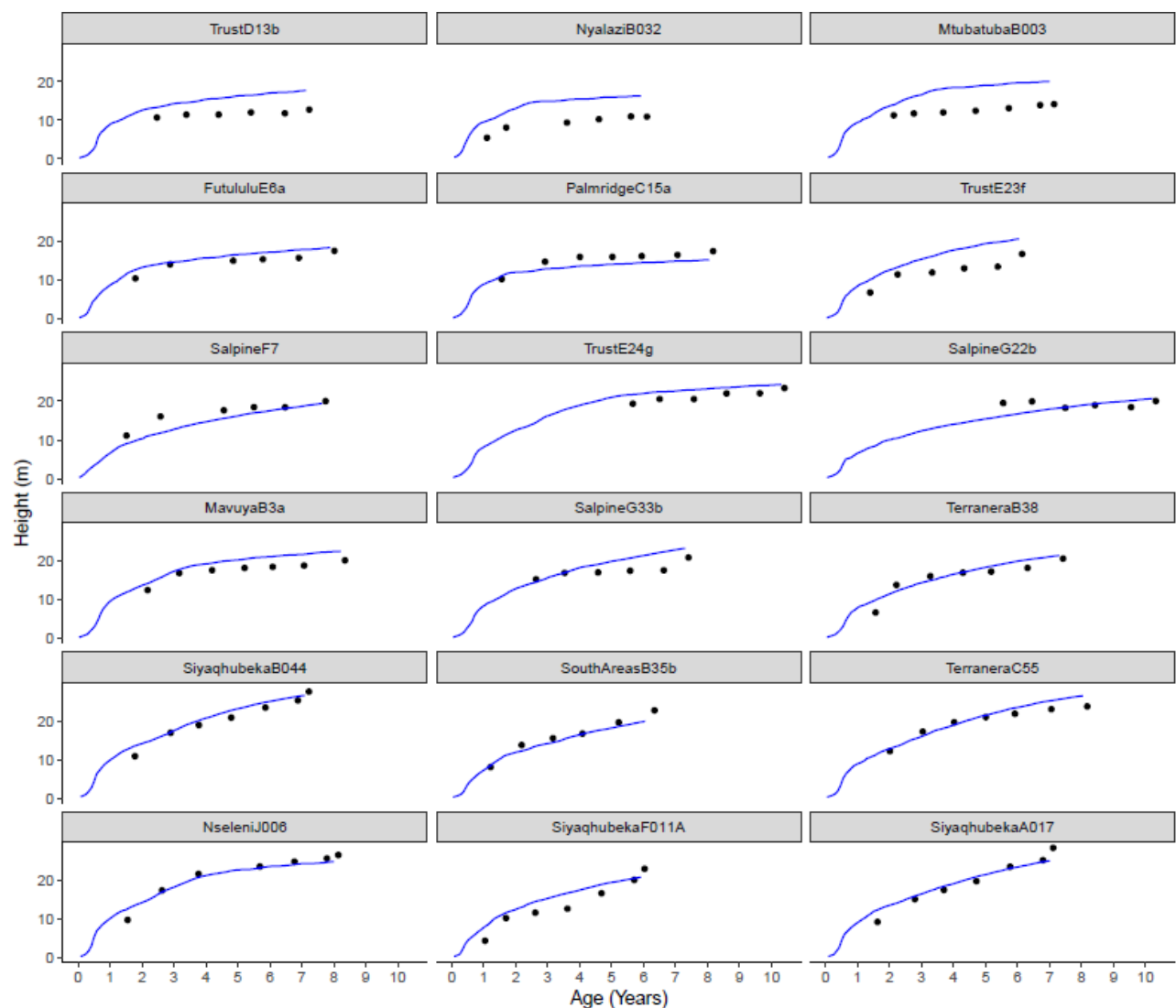


Figure 4.16: Observed (dots) and predicted (line) height trajectories using long term mean weather data.

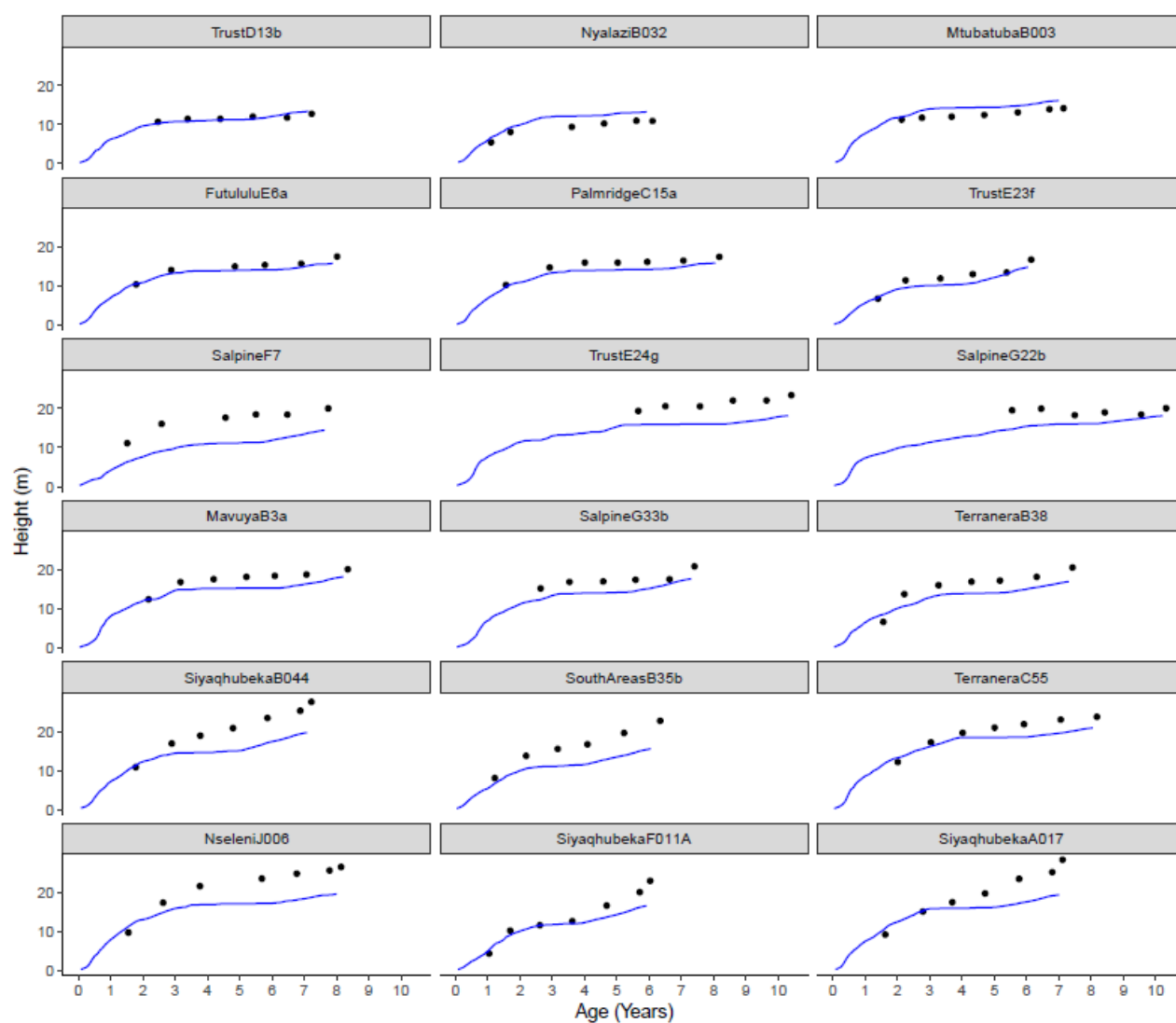


Figure 4.17: Observed (dots) and predicted (line) height trajectories using data from actual stations between 2008 - 2018.

4.7.2.3. Stand volume trajectory

Overall, using actual data from 2008 – 2018 led to better correlation of stand volume than when using long term mean data with multiple $R^2 = 69\%$ (*Figure 4.18*) in the former and multiple $R^2 = 62\%$ (*Figure 4.19*) in the latter case. Using long-term conditions stand volume was overpredicted in 66% of sites and correctly estimated for Salpine F7 and Salpine G22b (*Figure 4.20*). The overestimation of stand volume in the long-term conditions is expected because in reality, these sites will be experiencing severe drought period in 2015/2016. When the actually experienced conditions were used for the modelling, however, the volumes were under-estimated by a very large margin (*Figure 4.21*). This occurred at several sites, and particularly at the high MAI₂₀₁₈ sites, namely Siyaqhubeka A017, Siyaqhubeka B044, Siyaqhubeka F011A, and South Areas B35b which reduced the multiple R^2 with both the long-term monthly conditions and actual experienced daily conditions. Nyalazi B032 and Mtubatuba B003 was slightly over-predicted and Trust D13b was perfectly fitted to the observed stand volume projectory. As discussed previously, this was in large part due to the model overly penalising sites during the dry period when, in reality, at the faster growing sites growth continued during the dry years. This is interesting because it may indicate that some sites had access to water through the drought which could not be captured with the information available for model initialisation..

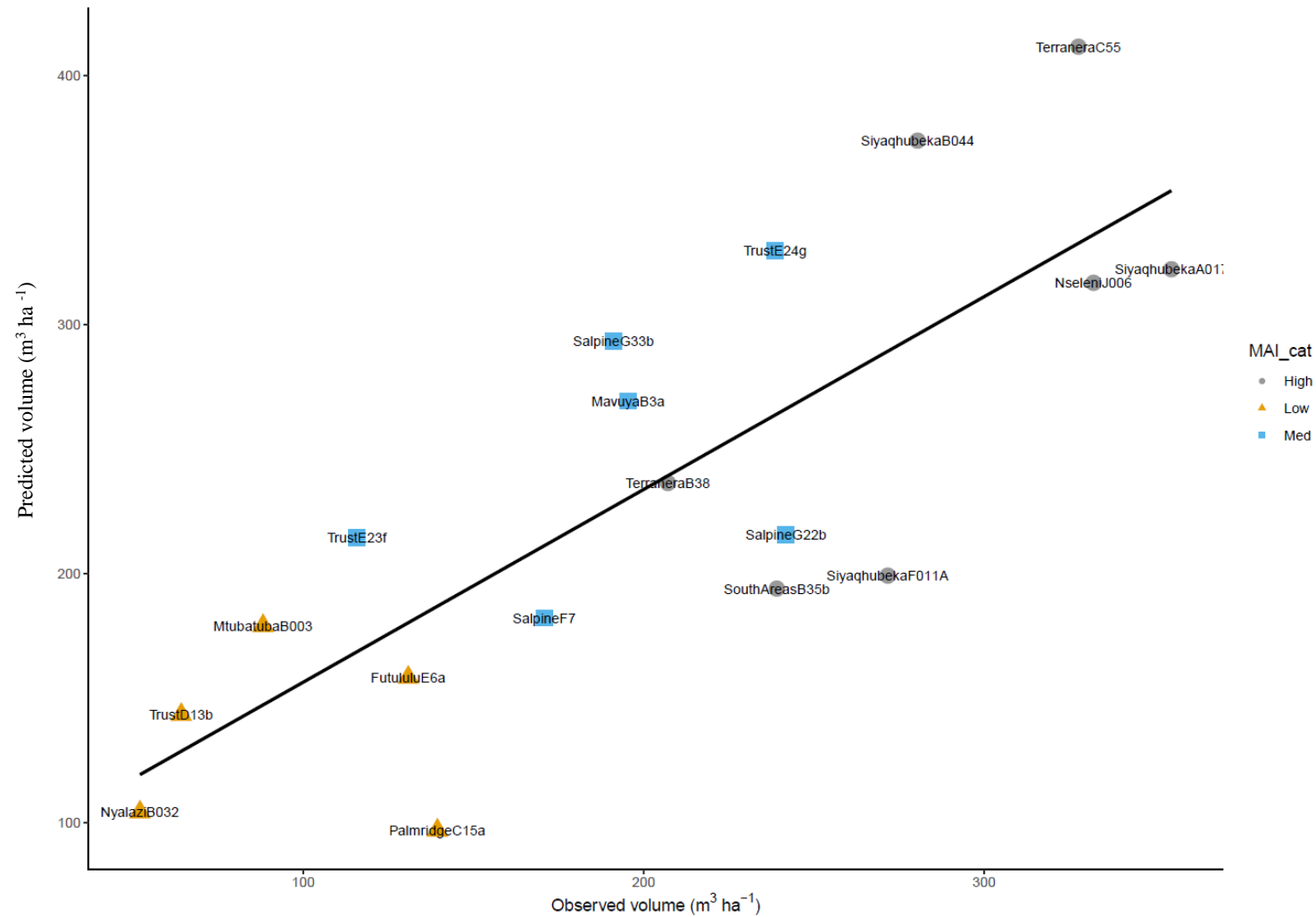


Figure 4.18: Observed and predicted stand volumes (as measured on July 31st, 2018) using long-term mean weather data. MAI_cat is the mean annual increment category defined in Section 4.4.

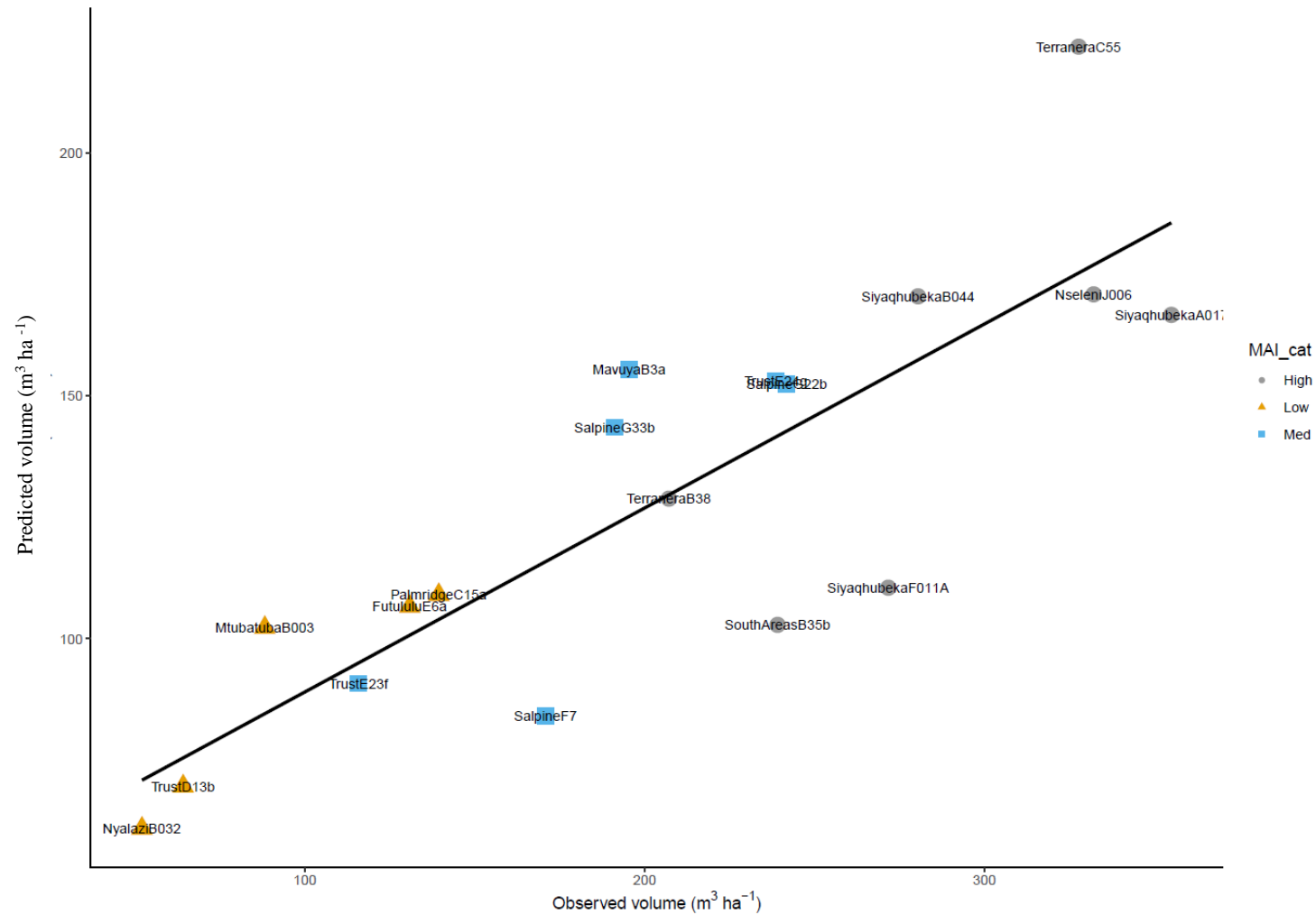


Figure 4.19: Observed and predicted stand volumes (as measured on July 31st, 2018) using weather data from actual stations between 2008 and 2018. MAI_cat is the mean annual increment category defined in Section 4.4.

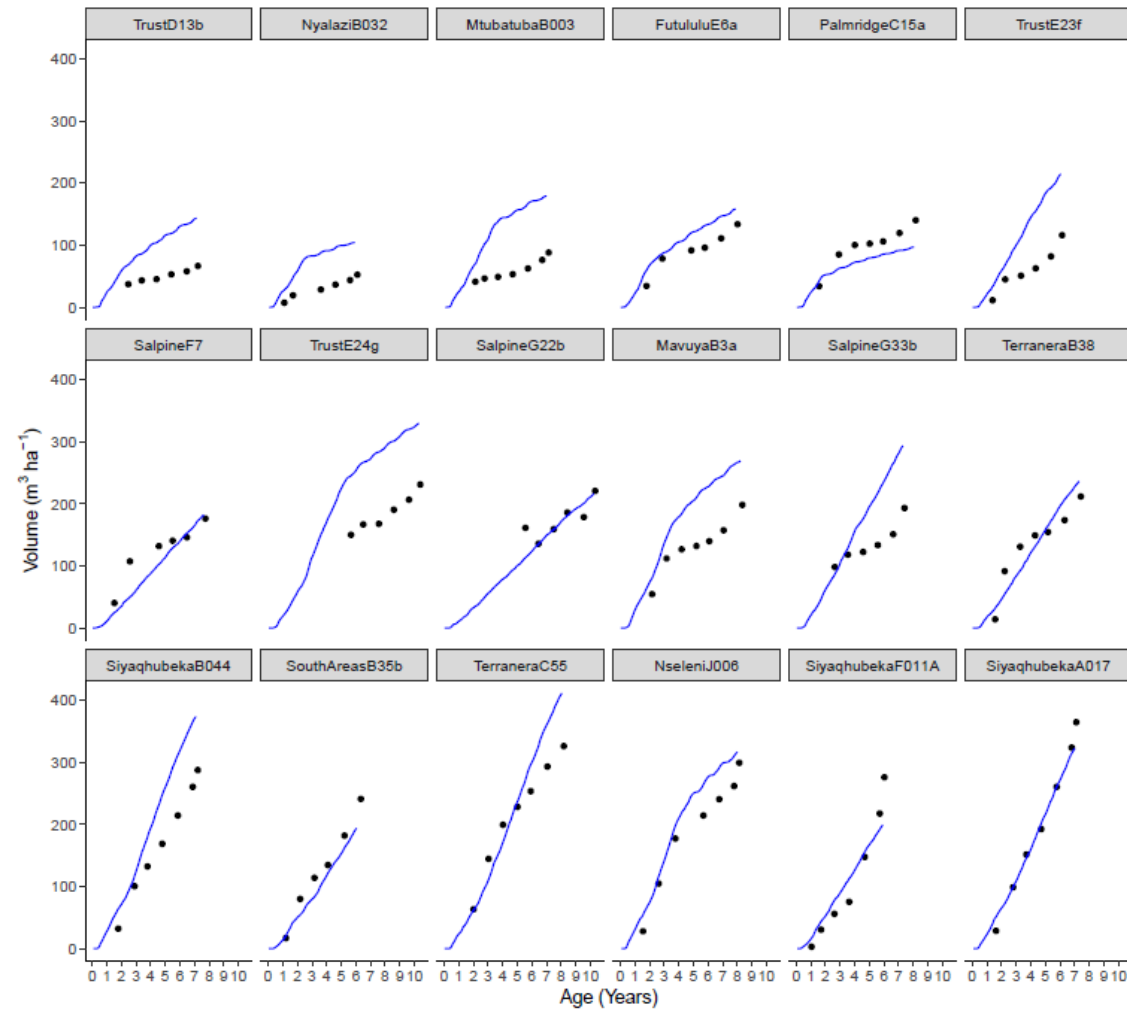


Figure 4.20: Observed (dots) and predicted (line) stand volume trajectories of *Eucalyptus grandis* x *urophylla* using long-term mean monthly data.

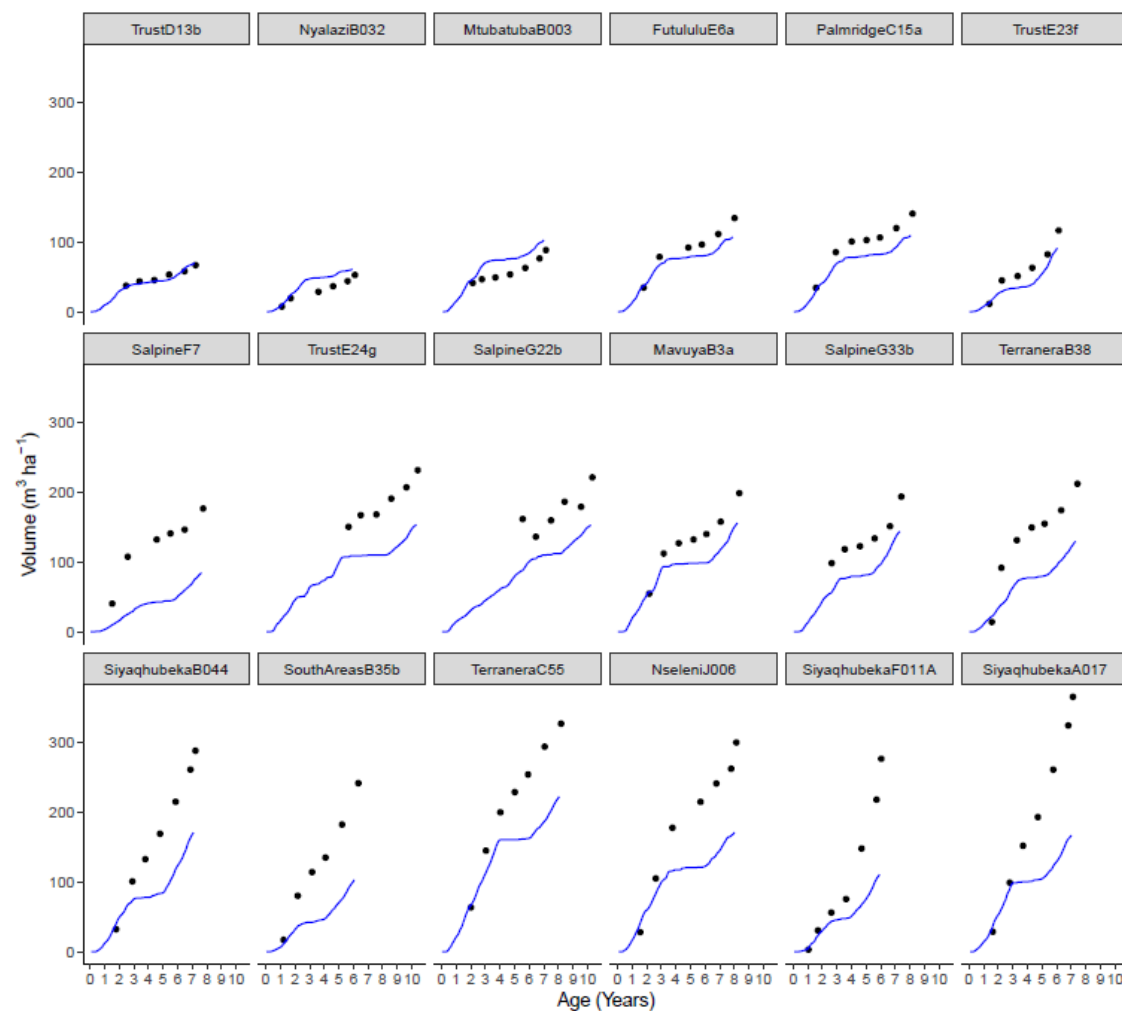


Figure 4.21: Observed (dots) and predicted (line) stand volume trajectories of *Eucalyptus grandis* x *urophylla* using data from actual weather stations between 2008 and 2018.

4.7.2.4. Leaf area index trajectory

Leaf area index (LAI) from CABALA was overestimated for several sites compared to MODIS estimates, whilst 33% of the sites LAI occurred in the range of the LAI estimated by the MODIS product (**Figure 4.22**). It is notable when comparing against MODIS that the pixel size is large and would have included (in many cases) other trees not only those in the compartments being modelled. Nonetheless, and importantly, the CABALA model allowed for a fair estimate of detecting and simulating the drop of LAI which occurred widely during the 2014-2015 drought conditions observed in this study (**Figure 4.23**). Notably, it was the faster growing sites where LAI drops did not occur markedly in reality, yet were predicted by the model. There are three ways which drought effects crown foliage in the CABALA model (2004). The first effect is that foliage growth discontinues when “pre-dawn water potential at which new foliage initiation discontinues” is reached. Foliage growth reduction results in not only the discontinuation of the crown horizontal growth but also delay in canopy closure in younger stands. The second drought response in CABALA is that when drought stress is extended, the sapwood loses its ability to sustain the crown foliage and causes the crown to shed some of its foliage, hence the drop of LAI in the actually experienced conditions. The third effect is that the CERES submodel in CABALA responds to water stress by reducing the nitrogen mineralisation rate. This means that less nitrogen would be transported to the crown foliage, as seen in **Section 4.5** (that leaf area is directly dependent on nitrogen concentration), and sites will have lower LAI as observed in **Figure 4.23**.

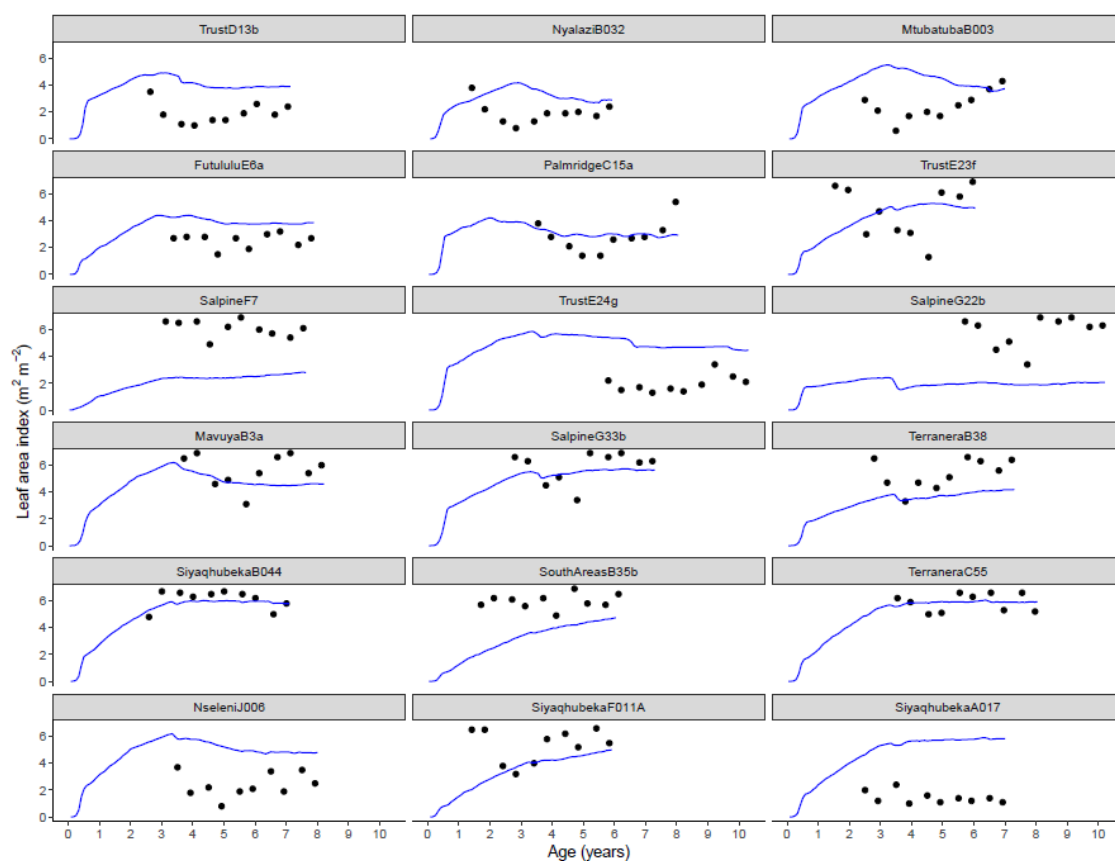


Figure 4.22: Observed LAI as derived from MODIS (black dots) and predicted (line) leaf area index trajectories using long-term mean weather data.

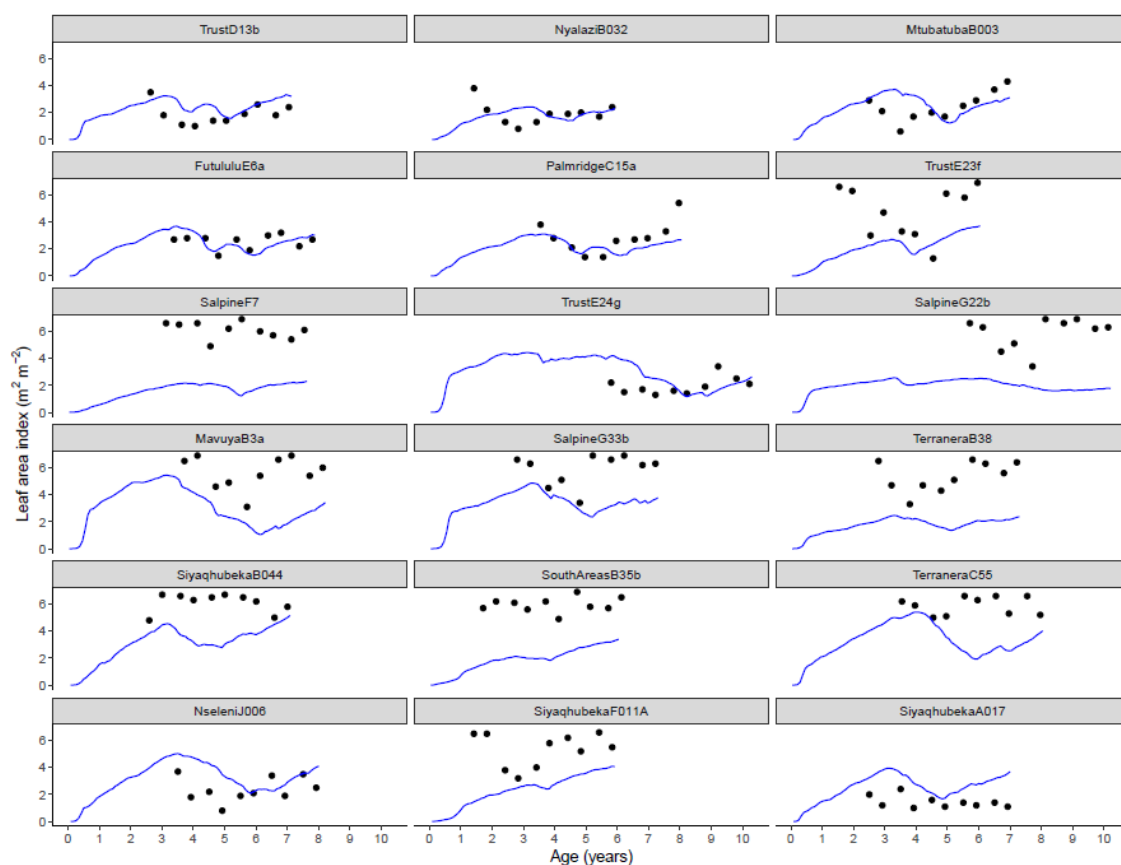


Figure 4.23: Observed LAI as derived from MODIS (black dots) and predicted (line) leaf area index trajectories using data from actual weather stations between 2008 and 2018.

4.7.3. Challenges faced with the CABALA model

The CABALA model did not predict mortality in any of the 18 sites; this is misleading because (although it was not high) there was some mortality observed in some sites as indication in *Section 4.4, Figure 4.9*. There reason for unpredicted mortality could be a parameter issue, particularly the $W_{S \times 1000}$, size of largest possible individual tree (kg) at 1000 stems ha^{-1} . This $W_{S \times 1000}$ parameter forces the model to estimate mortality when reduced. The largest possible individual tree observed in “Marie-Curie CFF” sample plots was 286.34 kg which is close to the $W_{S \times 1000}$ kg mentioned in Battaglia et al (2004). Even though the 286.34 kg was not used in the new *Eucalyptus grandis x urophylla* final parameter set as it did not truly represent the $W_{S \times 1000}$ parameter definition; 286.34 kg was still too high to cause the model to not estimate mortality. The non-predicted mortality by the model could be the reason for not getting stand volume observed in some sites like South Areas B35b and Siyaqhubeka F011A as mortality may lead to either an overestimation or an underestimation of productivity.

Aerosols in the Zululand region, as mentioned, can lead to high nitrogen deposition. The CABALA model does not capture the atmospheric nitrogen of 10-11 kg nitrogen/ha per annum reported by Dovey et al (2011) because the CERES-N sub-model in CABALA is not complex enough to accommodate sites with poor nutrients and atmospheric nitrogen deposition. Of course, the information are also very difficult to acquire or estimate.

Estimation of soil depth is likely to be an issue. Actual soil depth of Kwambonambi sites are hard to obtain, but it is possible that soils in the region can be as deep as 30m (Dovey, et al., 2011). In spite of this, in our study, we generally estimated a value of only 6m. This was in part because the *Eucalyptus grandis x urophylla* hybrid, in general rule does not deeply explore soil because of the character of the rooting cuttings. This is also generally a problem

in plants generated from macro-cuttings (Gonçalves et al. (2008) and Souza (2002). At several sites, where wind had caused uprooting of trees, it was clear that the root ball was small in these trees, possibly not even extending deeper than 1 m. There are instances in Kwambonambi region where water table is close to the surface, this of course have a major effect on the growth during drought. It is possible that some of the study sites had water table, but there was no clear evidence of this.

CONCLUSIONS

The primary objective of the research reported in this thesis was to partially parameterise and test the CABALA process-based growth model under a range of conditions for the important *E. grandis x urophylla* hybrid in South Africa. Data was obtained for 18 sites for this purpose and simulations run using two sources of weather data, namely long term means weather data and actual data from the period of growth of study sites. Overall, the CABALA process-based model was initiated and tested successfully for *Eucalyptus grandis x urophylla* plantations located in the sub-tropical Zululand region.

CABALA proved to be sensitive to various aspects of the input data, including the quality, reliability and specificity of the data. This is a challenge, especially in regard to soil depth and weather data input. The soil depth of the study sites in this thesis was not precisely known, and the uncertainty of rooting depth exacerbated this. Further, Zululand soils are inherently relatively infertile, yet there is also likely to be some level of aerial nitrogen deposition in the region which may play a role. The CABALA model was not designed to estimate aerial nitrogen deposition and the issue of nitrogen deposition was therefore not accommodated in the CABALA.

A major issue is weather data. Using long term data ignores the critical problem of within-rotation drought. However, there is a major shortage of real weather data, and no clear solution in terms of interpolated weather data products. Many compartments in this study had to “share” weather stations due to shortage of weather stations in that site. This challenge reduced the quality of the daily weather data and thus the stand production estimations in CABALA. It is important to note that Mondi (Ltd) and Sappi (Ltd) are in a process of installing more weather stations into their plantations and perhaps in coming decades there will be better daily weather data to incorporate in process-based models like CABALA. An

improved daily weather data quality will surely result to improved stand volume, mean diameter and mean height predictions.

The *E. globulus* parameter set from Battaglia et. al., (2004) resulted in underpredictions when used unchanged to estimate stand growth predictions for *GU*. However, the *E. globulus* parameter set is a good place to start from with species parameterisation for CABALA, especially for eucalypts species and hybrids. Because of the high numbers of parameters which must be estimated in CABALA, a formal sensitivity analysis can guide parameter focus. Although not done in the present study, a sensitivity analysis for the *GU* resource in Zululand will likely provide a guide for further work on CABALA.

The new parameter set for *GU* developed in this research did give promising predictions of stand volume, mean diameter, mean height, and leaf area index changes in drought and abundant rainfall events. But there was still a nagging level of underestimation, particularly at productive sites, due largely to a major “penalising” effect during the drought. That is, the model assumed too much of a drought effect. Possibly, some parameter adjustment would help this further. As more reliable physiological parameters are available for this hybrid, especially physiological parameters on respiration and photosynthesis models used in CABALA, this may improve. Better estimation of soil exploration is also a major aspect to be considered, but most importantly, better understanding of the below ground carbohydrate allocation and its drivers is also surely needed.

The CABALA model did not predict stand mortality, which was misleading because there was actual mortality observed in a number of sites (see **Section 4.4**). This weakness has also been reported by Pinkard et al., (2014) as the model tended to underestimate mortality in rates in permanent sample plots infested by pests. This is a weakness that opens an area further research and shows room of improvement for CABALA.

But it would seem that this type of model may well be useful for supporting management decisions in commercial plantations. The CABALA model can also be used as a research tool in parallel with empirical models to understand risk and environmental responses in forests. Provided that the parameterisation- drive continues, CABALA could, potentially, be incorporated as a planning tool for exploring which species or hybrids have potential to be planted in certain areas in present weather conditions and future weather conditions, under different scenarios of climate change.

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APPENDIX A: CABALA SITE DESCRIPTION

INPUT AND PARAMETERS

Table A-1: Required site description input data for simulation of site production with CABALA.

Climate	Units
For daily application:	
Daily maximum temperature	°C
Daily minimum temperature	°C
Daily radiation	MJ PAR m ⁻² ground per day
Daily rainfall	mm
For monthly uses:	
Average monthly maximum temperature	°C
Average monthly minimum temperature	°C
Highest recorded monthly maximum temperature	°C
Lowest recorded monthly minimum temperature	°C
Mean monthly rainfall	mm
Mean number of rain days per month	Days
Other atmospheric	
Partial pressure of atmospheric CO ₂	ppm
Soil factors	
User-defined soil layers:	
Susceptibility to water logging	Yes or No
Thickness of user defined horizon 1, 2, 3, ...	cm
Soil texture of user defined horizon 1, 2, 3...	%
Water holding capacity of horizon 1, 2, 3...	kg H ₂ O m ⁻² ground
Proportion of layers 1, 2, 3... comprising stones	0-1
Thickness of any impeding layer	cm
Hardness of any impeding layer; relative scale	0-10
Soil layers for nitrogen mineralisation and soil evaporation:	
Organic matter content of 0-10, 10-20, 20-50 cm layers	%
C:N ratio of 0-10, 10-20, 20-50 cm layers	-
Bulk density of 0-10, 10-20, 20-50 cm layers	g cm ⁻³

pH of 0-10, 10-20, 20-50 cm layers	-
Site location	
Site latitude	o
Regime	
Tree spacing:	
Intra- row spacing	m
Inter- spacing	m
Trees per row	-
Rows per block	-
Distance between tree blocks in row direction	m
Distance between tree blocks perpendicular to row	m
direction	
Rows orientation	o
Treatments:	
Establishment date	YYYY/MM/DD
Fertiliser treatment	kg/ha
Farrows	-
Thinning	trees ha ⁻¹
Harvesting date	YYYY/MM/DD

Table A-2: A description of CABALA parameters according to Battaglia et al.,(2004).

Parameter	Meaning	Units
<i>Single leaf light response</i>		
α_0	Value of quantum yield at base temperature (20°C)	mol CO ₂ mol ⁻¹ (quanta)
α_1	Temperature sensitivity of quantum yield	°C ⁻¹
A^*_{opt}	Intercellular CO ₂ saturated rate of carbon assimilation	mmol CO ₂ m ⁻² leaf s ⁻¹
T^*_{opt}	Optimum temperature for photosynthesis	°C
k	Canopy light extinction coefficient	M ² ground m ⁻² leaf
θ	Shape of single- leaf light response curve	-
$t_{1/2-}$	Determines sensitivity of assimilation to low diurnal temperatures	°C
$t_{1/2+}$	Determines sensitivity of assimilation to high diurnal temperatures	°C
Γ^*	Photosynthetic CO ₂ compensation point	Pa
<i>Photosynthetic temperature acclimation parameters</i>		
t	Determines extent of seasonal acclimation of T _{opt}	
T_{pref}	Parameter determining seasonal acclimation of T _{opt}	°C

$t^*_{1/2-}$	Determines acclimation of A_{opt} to low seasonal temperatures	$^{\circ}\text{C}$
$t^*_{1/2+}$	Determines acclimation of A_{opt} to high seasonal temperatures	$^{\circ}\text{C}$
<i>Parameters for foliar respiration</i>		
k_{dav}	Temperature rate constant for foliar respiration	$^{\circ}\text{C}^{-1}$
r_{d0}	Value of foliar respiration at temperature $T = T_0$	$\text{mmol CO}_2, \text{m}^{-2}$ leaf s^{-1}
k_{d0}	Value of k_{dav} at temperature $T = T_0$	$^{\circ}\text{C}^{-1}$
k_{d1}	Temperature sensitivity of k_{dav}	$^{\circ}\text{C}^{-1}$
<i>Single leaf and canopy conductance parameters</i>		
g_0	Minimum stomatal conductance	$\text{mol H}_2\text{O m}^{-2}$ ground s^{-1}
g_1	Determines VPD (D) dependency of water- use efficiency	$\text{mol H}_2\text{O m}^{-2}$ ground s^{-1}
g_B	Maximum tree canopy boundary layer conductance: upper canopy foliage	$\text{mol H}_2\text{O m}^{-2}$ ground s^{-1}
f_{d1}	Multiplier in D: g_s relationship	-
f_{d2}	Exponent in D: g_s relationship	kPa^{-1}
f_{y1}	Multiplier in soil water potential: g_s relationship	
f_{y2}	Exponent in soil water potential: g_s relationship	MPa^{-1}

f_{Y3}	Number of days today's water stress influence conductance	Days
r_{Q-c}	Fraction of reflection that is reflected by crown	-
<i>Soil evaporation parameters</i>		
E_s^*	Maximum daily soil evaporation rate: supply side	kg H ₂ O m ⁻² ground per day
e_0	Defines relationship between fine root density and water uptake efficiency	kg DM m ⁻² ground
g_{Bsoil}	Maximum soil boundary layer conductance	mol H ₂ O m ⁻² ground s ⁻¹
g_{Csoil}^*	Maximum rate of soil conductance	mol H ₂ O m ⁻² ground s ⁻¹
r_{Q-s}	Fraction of radiation that is reflected by soil	-
<i>Rainfall interception model</i>		
I_L	Scalar between leaf area index and interception	kg H ₂ O m ⁻² leaf
I^*	Maximum proportion of any rainfall event intercepted by close canopy	-
<i>Plant water status vs, PASW relationship</i>		
ψ	Lowest pre- dawn water potential to which trees fall	MPa
ψ^+	Pre- dawn leaf water potential at field capacity	MPa
<i>Plant and environment stresses</i>		

a_{wl}	Fraction by which waterlogging reduces photosynthesis rate	-
W_{WL}	Critical relative available soil water for waterlogging	-
Y_{FR-WL}	Number of days of waterlogging before all fine roots killed	Days
Y_{CR-WL}	Number of days of waterlogging before all coarse roots killed	Days
U_{N-WL}	Fractional reduction in nitrogen uptake due to waterlogging	-
F_{R-P}	Temperature range between 0 and 100%	$^{\circ}\text{C}$
F_{D-F-UH}	Temperature at which 50% foliar damage in unhardened material	$^{\circ}\text{C}$
F_{D-F-H}	Temperature at which 50% foliar damage in fully hardened material	$^{\circ}\text{C}$
F_{R-F}	Temperature range 0 – 100% foliar damage from low temperature	$^{\circ}\text{C}$
F_{D-P-UH}	Temperature at which 50% photosynthetic damage in unhardened material	$^{\circ}\text{C}$
F_{D-P-H}	Temperature at which 50% photosynthetic damage in fully hardened material	$^{\circ}\text{C}$
F_{a-P}	Constant in definition of photosynthetic frost hardiness	$^{\circ}\text{C}$
F_{b-P}	Constant in definition of photosynthetic frost hardiness	$^{\circ}\text{C}$

F_{c-P}	Constant in definition of photosynthetic frost hardness	$^{\circ}\text{C}$
F_{a-F}	Constant in definition of foliar frost hardness	$^{\circ}\text{C}$
F_{b-F}	Constant in definition of foliar frost hardness	$^{\circ}\text{C}$
F_{c-F}	Constant in definition of foliar frost hardness	$^{\circ}\text{C}$
F_p	Exponent of frost impact factor defining long- term photosynthetic impact	-
F^+	Number of days for full photosynthetic recovery from long term frost damage	Days
F_T	Average daily temperature below which photosynthetic recovery reduced	$^{\circ}\text{C}$
K_a	Water potential threshold for xylem embolism	MPa
K_b	Pre- dawn water potential at which all xylem embolised	MPa
RWC_0	Amount of soil water within root zone above which no canopy evaporative constraint	$\text{Kg H}_2\text{O m}^{-2}$ ground
ψ_F	Pre- dawn water potential at which new foliage initiation ceases	MPa
<i>Nitrogen effects in photosynthesis and specific leaf area</i>		
N_{FXopt}	Optimum foliage nitrogen concentration at top of canopy	$\text{kg N kg}^{-1} \text{ DM}$
N_0	Minimum foliage N for positive net photosynthesis	$\text{kg N kg}^{-1} \text{ DM}$
k_N	Attenuation of N through canopy with cumulative L	$\text{m}^2 \text{ ground m}^{-2} \text{ leaf}$

σ_0	Specific leaf area for non- nitrogen limited leaves	$\text{m}^2 \text{kg}^{-1}$
σ_1	Lower limit of specific leaf area	$\text{m}^2 \text{kg}^{-1}$
b_σ	Rate of change of specific leaf area with leaf nitrogen concentration	$\text{kg DM kg}^{-1} \text{N}$
<i>Tissue nitrogen parameters</i>		
N_B	Average branch nitrogen concentration	$\text{g N g}^{-1} \text{DM}$
N_{S-SW}	Average stem sapwood nitrogen concentration	$\text{g N g}^{-1} \text{DM}$
N_{S-HW}	Average heartwood (root and stem) nitrogen concentration	$\text{kg N kg}^{-1} \text{DM}$
N_{Bk}	Average bark nitrogen concentration	$\text{kg N kg}^{-1} \text{DM}$
N_{fR}	Average fine root nitrogen concentration	$\text{kg N kg}^{-1} \text{DM}$
N_{cR}	Average coarse root nitrogen concentration	$\text{kg N kg}^{-1} \text{DM}$
α	Fraction of nitrogen re- translocated from tissues on senescence	$\text{kg N kg}^{-1} \text{DM}$
δN^*	Maximum increase/ decrease in foliar N concentration per day	$\text{kg N kg}^{-1} \text{DM per day}$
u_0	Defines relationship between fine root density and nitrogen uptake efficiency	$\text{kg DM m}^{-2} \text{ground}$
<i>Annual biomass loss rate</i>		
Y_F	Reciprocal of maximum foliage longevity	Per year
Y_{Bk}	Reciprocal of maximum bark longevity	Per year

Y_{fR}	Reciprocal of maximum fine roots longevity	Per year
<i>Allometrics and stand architecture</i>		
ρ_w	Mean density of stem, branch and coarse root wood	kg DM m ⁻³
β_{cR}	Ratio of below- ground biomass to above- ground biomass	kg DM m ⁻³
β_{w3L1}	Multiplier in relationship between stem sapwood cross-sectional area and L	-
β_{w3L2}	Exponent in relationship between stem sapwood cross-sectional area and tree height	-
β_{w3L3}	Exponent in relationship between stem sapwood cross-sectional area and L	-
β_{w3Bk1}	Multiplier in relationship between bark mass and stem mass	-
β_{w3Bk2}	Exponent in relationship between bark mass and stem mass	-
β^*_{Bk}	Maximum ratio bark/(bark + stem)	kg bark kg ⁻¹ stem wood
β_{v1}	Multiplier in volume equation	-
β_{v2}	Exponent of height in volume equation	-
β_{v3}	Exponent of basal area in volume equation	-
β_{w1}	Multiplier in stem height to diameter ratio equation	-

β_{w2}	Exponent in stem height to diameter ratio equation	-
β_{w3}	Exponent stem height to diameter ratio equation	-
ϕ	Average branch angle from the horizontal	0
x	Volume of branch as proportion of cylinder with same basal diameter and length	-
$W_{S \times 1000}$	Size of largest possible individual tree (kg) at 1000 stems ha ⁻¹	kg
<i>Soil resource uptake</i>		
E^*_T	Potential maximum rate of stand water use	kg H ₂ O m ² ground per day
∂z^*_R	Potential maximum annual vertical root growth	cm per year
<i>For N driven respiration</i>		
r_C	Construction respiration ration	-
r_{0-cR}	Specific coarse- root sapwood respiration	kg C kg ⁻¹ N per year
r_{0-B}	Specific branch sapwood respiration	kg C kg ⁻¹ N per year
r_{0-fR}	Specific fine- root sapwood respiration	kg C kg ⁻¹ N per year
r_{0-S}	Specific stem sapwood respiration	kg C kg ⁻¹ N per year

Q_{10}	Q_{10} for respiration	-
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Table A-3: The parameter set developed for GU. Parameters with no author are those that were altered from the *E. globulus* parameter set from Battaglia et al., (2004)

Parameter	Units	Value	Author
Single leaf light response			
α_0	mol CO ₂ mol ⁻¹ (quanta)	0.05	Battaglia et al.,(2004)
α_1	°C ⁻¹	0.016	Battaglia et al.,(2004)
A^*_{opt}	mmol CO ₂ m ⁻² leaf s ⁻¹	56	Battaglia et al.,(2004)
T^*_{opt}	°C	24	
k	M ² ground m ⁻² leaf	0.5	Battaglia et al.,(2004)
θ	-	0.95	Battaglia et al.,(2004)
$t_{1/2-}$	°C	11	Battaglia et al.,(2004)
$t_{1/2+}$	°C	11	Battaglia et al.,(2004)
Γ^*	Pa	45	Battaglia et al.,(2004)
Photosynthetic temperature acclimation parameters			
t		0	Battaglia et al.,(2004)
T_{pref}	°C	23	Battaglia et al.,(2004)
$t^*_{1/2-}$	°C	999	Battaglia et al.,(2004)
$t^*_{1/2+}$	°C	999	Battaglia et al.,(2004)
Parameters for foliar respiration			
k_{dav}	°C ⁻¹	0.015	
r_{d0}	mmol CO ₂ , m ⁻² leaf s ⁻¹	1	Battaglia et al.,(2004)
k_{d0}	°C ⁻¹	0.09	Battaglia et al.,(2004)
k_{d1}	°C ⁻¹	0.00375	
Single leaf and canopy conductance parameters			
g_0	mol H ₂ O m ⁻² ground s ⁻¹	0.01	Battaglia et al.,(2004)
g_1	mol H ₂ O m ⁻² ground s ⁻¹	2	Battaglia et al.,(2004)
g_B	mol H ₂ O m ⁻² ground s ⁻¹	4	Battaglia et al.,(2004)
f_{d1}	-	1.21	
f_{d2}	kPa ⁻¹	0.3	Battaglia et al.,(2004)
f_{Y1}		1.2	
f_{Y2}	MPa ⁻¹	-1	Battaglia et al.,(2004)
f_{Y3}	Days	8	Battaglia et al.,(2004)

r_{Q-C}	-	0.3	Battaglia et al.,(2004)
Soil evaporation parameters			
E_s^*	kg H ₂ O m ⁻² ground per day	3	Battaglia et al.,(2004)
e_0	kg DM m ⁻² ground	1	Battaglia et al.,(2004)
g_{Bsoil}	mol H ₂ O m ⁻² ground s ⁻¹	4	Battaglia et al.,(2004)
g_{Csoil}^*	mol H ₂ O m ⁻² ground s ⁻¹	0.4	Battaglia et al.,(2004)
r_{Q-S}	-	0.3	Battaglia et al.,(2004)
Rainfall interception model			
I_L	kg H ₂ O m ⁻² leaf	0.3	Battaglia et al.,(2004)
I^*	-	0.75	Battaglia et al.,(2004)
Plant water status vs, PASW relationship			
ψ	MPa	-4.2	
ψ^+	MPa	-0.2	
Plant and environment stresses			
a_{wl}	-	0.5	Battaglia et al.,(2004)
W_{WL}	-	0.9	Battaglia et al.,(2004)
Y_{FR-WL}	Days	180	Battaglia et al.,(2004)
Y_{CR-WL}	Days	1095	Battaglia et al.,(2004)
U_{N-WL}	-	0.5	Battaglia et al.,(2004)
F_{R-P}	°C	5	Battaglia et al.,(2004)
F_{D-F-UH}	°C	-3	Battaglia et al.,(2004)
F_{D-F-H}	°C	-7	Battaglia et al.,(2004)
F_{R-F}	°C	5	Battaglia et al.,(2004)
F_{D-P-UH}	°C	0	Battaglia et al.,(2004)
F_{D-P-H}	°C	-2	Battaglia et al.,(2004)
F_{a-P}	°C	-3	Battaglia et al.,(2004)
F_{b-P}	°C	0.5	Battaglia et al.,(2004)
F_{c-P}	°C	0.03	Battaglia et al.,(2004)
F_{a-F}	°C	-26	Battaglia et al.,(2004)
F_{b-F}	°C	3	Battaglia et al.,(2004)
F_{c-F}	°C	0.02	Battaglia et al.,(2004)
F_p	-	0.15	Battaglia et al.,(2004)
F^+	Days	14	Battaglia et al.,(2004)
F_T	°C	15	Battaglia et al.,(2004)

K_a	MPa	-2.5	Battaglia et al.,(2004)
K_b	MPa	-5	Battaglia et al.,(2004)
RWC_0	Kg H ₂ O m ⁻² ground	250	Battaglia et al.,(2004)
ψ_F	MPa	-1	Battaglia et al.,(2004)
Nitrogen effects in photosynthesis and specific leaf area			
N_{FXopt}	kg N kg ⁻¹ DM	0.02	Battaglia et al.,(2004)
N_0	kg N kg ⁻¹ DM	0.002	Battaglia et al.,(2004)
k_N	m ² ground m ⁻² leaf	0.5	Battaglia et al.,(2004)
σ_0	m ² kg ⁻¹	11	Battaglia et al.,(2004)
σ_I	m ² kg ⁻¹	3.81	
b_σ	kg DM kg ⁻¹ N	90	
Tissue nitrogen parameters			
N_B	g N g ⁻¹ DM	0.002	Battaglia et al.,(2004)
N_{S-SW}	g N g ⁻¹ DM	0.001	Battaglia et al.,(2004)
N_{S-HW}	kg N kg ⁻¹ DM	0.0001	Battaglia et al.,(2004)
N_{Bk}	kg N kg ⁻¹ DM	0.002	Battaglia et al.,(2004)
N_{fR}	kg N kg ⁻¹ DM	0.01	Battaglia et al.,(2004)
N_{cR}	kg N kg ⁻¹ DM	0.002	Battaglia et al.,(2004)
λ	kg N kg ⁻¹ DM	0.5	Battaglia et al.,(2004)
δN^*	kg N kg ⁻¹ DM per day	2.7397E-05	Battaglia et al.,(2004)
u_0	kg DM m ⁻² ground	2	Battaglia et al.,(2004)
Annual biomass loss rate			
Y_F	Per year	0.33	Battaglia et al.,(2004)
Y_{Bk}	Per year	0.1	Battaglia et al.,(2004)
Y_{fR}	Per year	1	Battaglia et al.,(2004)
Allometrics and stand architecture			
ρ_w	kg DM m ⁻³	0.5	
β_{cR}	kg DM m ⁻³	0.23	Battaglia et al.,(2004)
β_{w3L1}	-	0.96	Zhu et al.,(2015)
β_{w3L2}	-	0.8	Zhu et al.,(2015)
β_{w3L3}	-	0.37	Zhu et al.,(2015)
β_{w3Bk1}	-	10.69	Battaglia et al.,(2004)
β_{w3Bk2}	-	-0.394	Battaglia et al.,(2004)
β^*_{Bk}	kg bark kg ⁻¹ stem wood	0.16	

β_{v1}	-	0.6135	Battaglia et al.,(2004)
β_{v2}	-	0.968	Battaglia et al.,(2004)
β_{v3}	-	0.825	Battaglia et al.,(2004)
β_{w1}	-	142.6	
β_{w2}	-	-0.24	
β_{w3w3}	-	-0.007	
ϕ	0	42.16	
x	-	1.05	
W_{Sx1000}	kg	300	Battaglia et al.,(2004)
Soil resource uptake			
E^*_T	kg H ₂ O m ² ground per day	10	Battaglia et al.,(2004)
∂z^*_R	cm per year	250	Battaglia et al.,(2004)
For N driven respiration			
r_C	-	0.1	
r_{0-cR}	kg C kg ⁻¹ N per year	50	Battaglia et al.,(2004)
r_{0-B}	kg C kg ⁻¹ N per year	50	Battaglia et al.,(2004)
r_{0-fR}	kg C kg ⁻¹ N per year	100	Battaglia et al.,(2004)
r_{0-S}	kg C kg ⁻¹ N per year	50	Battaglia et al.,(2004)
Q_{10}	-	1.3	Battaglia et al.,(2004)

